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AND INDUSTRIAL WATER SUPPLY(U) SOUTHERN ILLINOIS UNIV
CARBONDALE DEPT OF GEOGRAPHY B DZIEGIELEWSKI ET AL.
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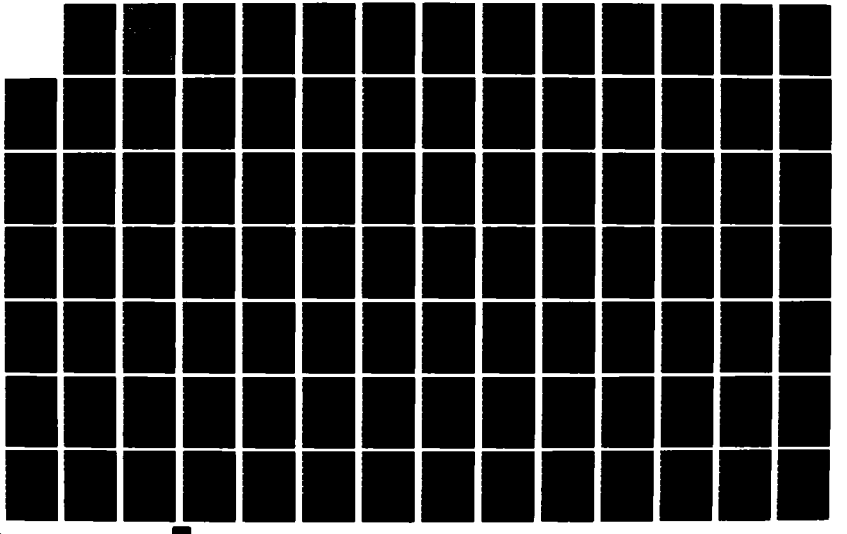

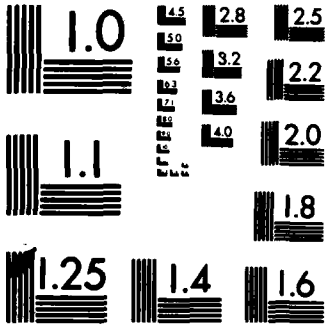

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: CR 83-C-3	2. GOVT ACCESSION NO.: H135430
3. RECIPIENT'S CATALOG NUMBER:	
4. TITLE (and Subtitle): The Evaluation of Drought Management Measures For Municipal and Industrial Water Supply	5. TYPE OF REPORT & PERIOD COVERED: Final
	6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): Benedykt Dziegielewski, Duane D. Baumann, John J. Boland	8. CONTRACT OR GRANT NUMBER(s):
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Southern Illinois University, Johns Hopkins University	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
11. CONTROLLING OFFICE NAME AND ADDRESS: Institute for Water Resources, Casey Building, Fort Belvoir, VA 22060	12. REPORT DATE: December 1983
	13. NUMBER OF PAGES: 132
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Drought, conservation, water supply planning.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report formulates and applies a planning method for determining optimal strategies for shortage mitigation in municipal and industrial water supplies. The report contains a review and analysis of drought planning literature.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

THE EVALUATION OF DROUGHT MANAGEMENT MEASURES FOR MUNICIPAL AND INDUSTRIAL WATER SUPPLY

Prepared for

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December, 1983

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ACKNOWLEDGEMENTS

In every stage of development, this report benefited from the constructive criticism of numerous persons. We are especially appreciative of the thorough reviews and many constructive suggestions of James Crews, who also provided the initial impetus for the project. Additional valuable assistance was also provided by other staff members of the U.S. Army Corps of Engineers: Donald B. Duncan, John Burns, Mike Krouse, Bob Daniel, Ming Tseng, Eugene Z. Stakhiv, and Jim Ballif. Suggestions and criticisms of Dr. Clifford Russell, the Resources for the Future, Inc., were very helpful in formulating the conceptual planning model described in this report. Also, many people were helpful in the preparation of this volume. Its production would have been virtually impossible without the dedicated and capable support of Barbara Pearson in typing both the early and the final versions of this volume. Russ Brodie provided us with valuable assistance in the preparation of the annotated bibliography. Finally, we want to thank John Langowski, who took his valuable time to edit and discuss several parts of this report.

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PREFACE

The overall purpose of this research project was to formulate and apply a planning method for determining optimal strategies for shortage mitigation in municipal and industrial water supplies.

The results of the study are presented in three separate units. The first represents the main body of this report. It contains a review and analysis of drought planning literature which has led to the formulation of a general conceptual planning model. This model referred to as drought optimization procedures (or the DROPS model) is summarized in Chapter I - Introduction, while the literature pertinent to the model application is reviewed in the subsequent four chapters. The second unit of the study represents an annotated bibliography of all the sources of literature that are applicable to drought contingency planning. An annotated bibliography is included as an appendix. Finally, the third unit of the study involved a prototypal application of the developed procedure for the city of Springfield, Illinois. A detailed documentation of data gathering and analysis involved in the preparation of the prototypal application are included as a separate volume.

Both these reports describe the findings, conclusions and independent judgment of the authors. These concepts and conclusions are not construed to necessarily represent the view of the Corps of Engineers.

CHAPTER I

INTRODUCTION

Objectives and Design

Drought contingency planning requires well quantified information on (1) climatological or engineering indicators to signal the onset of drought and to estimate the risk of supply shortage at each point of an actual drought event; (2) expected impacts of drought on both quantity and quality of water in supply sources; (3) the magnitude of increased drought period demands for water; and (4) planning procedures for development of drought management plans which incorporate legal, institutional, social, economic, and engineering standpoints.

This study addresses each of the dimensions of drought contingency planning through three specific objectives:

(1) development of an information base required in the evaluation of a large number of diversified drought management measures and their integration into specific drought management plans;

(2) formulation of a practical planning procedure that would permit a water manager to select the optimal strategy for minimizing economic impact of a water supply crisis by finding the best tradeoff between supplying additional water from various emergency sources and cutting back on water delivery by implementing water conservation programs; and

(3) illustrative application of the developed procedure.

A number of already existing planning concepts, procedures and measurement techniques that are applicable to these objectives are identified from the literature and summarized. These include: (1) procedures for alerting to a drought; (2) methods for assessing the magnitude of expected water supply deficit induced by drought (short-run streamflow prediction); (3) models for forecasting the increased water consumption related to drought conditions; (4) methods for estimating the costs of emergency water supplies; (5) procedures for the determination of potential demand reduction and supply conservation measures and the evaluation of their applicability, technical feasibility, social acceptability, implementation conditions, and cost-effectiveness; (6) methods for the determination of monetary losses associated with various cutbacks in water delivery to various user categories, and the water utility itself; and (7) mathematical optimization procedures including sensitivity analysis.

The following sections of this chapter (1) define the role of drought contingency planning within the framework of planning for municipal and industrial water supplies; (2) review of the conceptual planning frameworks proposed by various authors; (3) summarize the literature documenting emergency actions undertaken during drought induced water shortages by

various systems, and (4) formulate a tentative general procedure (algorithm) for the preparation of drought management plans. The techniques and methods applicable to the drought management are summarized and discussed in Chapters II through V. An appendix at the end of this volume contains an annotated bibliography on drought contingency planning.

Perspectives on Drought Contingency Planning

Relatively little has been done to formulate a comprehensive planning method that would allow a water planner or utility manager to formulate the "best" drought contingency plan. The decision criteria for applying emergency measures during severe water shortages must be preceded by full consideration of both the long- and the short-term alternatives chosen from possibly the largest array of alternative actions. Therefore, drought contingency planning should be incorporated into planning for urban water supply where it is given an equal consideration together with long-term water supply and water conservation. The following section attempts to summarize the role of drought contingency planning in the provision of adequate water supply. This section integrates the planning concepts found in literature into a prescriptive planning framework.

Planning for Urban Water Supply

A comprehensive approach to the evaluation of drought contingency measures calls for the consideration of emergency water supplies along with the demand reduction alternatives within the general framework of planning for urban water supply capacity (Figure 1). Although it is helpful to distinguish between the long-term and short-term aspects of water supply planning, in reality the two perspectives are inevitably linked and many researchers have attempted to define the criteria and procedures for developing an optimal strategy that would satisfy both the short-term and long-term objectives.

The long-term investment strategies for the provision of "adequate" urban water supplies should be evaluated according to the principles of planning for effective use of limited resources. The term "adequate" implies the principle of balancing the cost of supply additions and/or long-term water conservation programs against the expected damages that may result from recurrent droughts in the long run. This problem is complicated by unrestricted demands for water that grow over time. In deciding on the timing and sizes of additions to the supply system, a planner must determine the level of expected damages from temporary shortages of water in the long run. However, the damages that may result from a water shortage event are difficult to precisely estimate unless intensive data gathering is undertaken.

Traditionally, the capacity of water supply sources has been determined utilizing the concept of "safe yield" and reliability of supply. The safe yield is often understood as that output of a water supply project that can be maintained during a severe drought such as the worst drought in the historic record (or otherwise specified). The estimated probability of such a drought occurring in any one year defines the reliability of the safe yield, for example, 1/40 or 2.5 percent. A planner decides on this probability of failure by selecting a "design drought", i.e., a drought

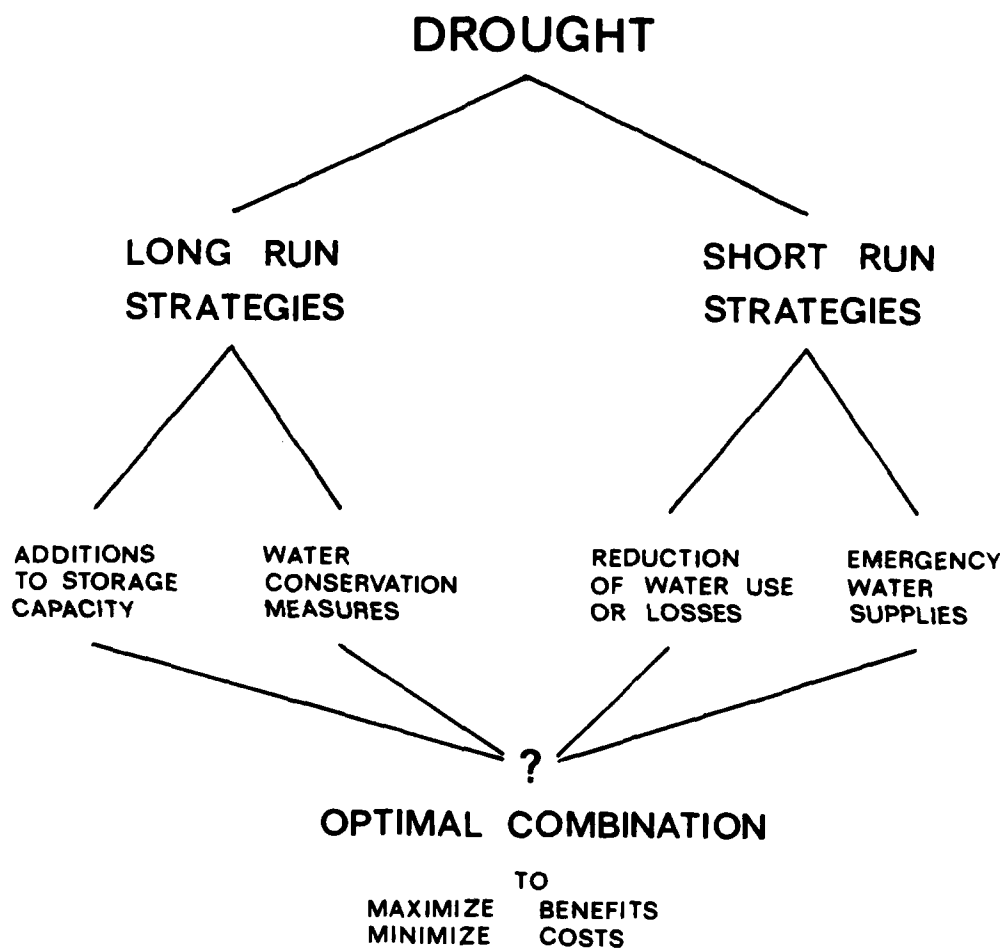

Figure 1. Two Dimensions of Drought Contingency Planning

with stated probability of occurrence, usually 1/20, 1/50, or 1/100, i.e. 5, 2, or 1 percent.

Selecting the "design drought" constitutes the most important decision in the whole planning process since it implicitly incorporates the magnitude of economic losses that may be incurred in the long run. Thus, the process of selecting the required reservoir storage begins with specifying "design drought," for example, a 100-year drought, and then assuming the required "safe yield" of the project equal to the level of demand at the end of the planning horizon. In the case of staged projects, timing and sizes of addition to source capacity may be found by applying the criterion of a minimum present value of all costs that are incurred in meeting the demand at all times except during the droughts which are more severe than the design drought.

Planning for short-term supply deficiencies is constrained by the physical dimensions of a water supply system. The "safe yield" of the system is only of limited value to a water manager. Although his system is designed to supply water at the specified safe yield during the design drought, the manager never knows how severe and how long the drought will last. In the case of reservoir storage, maintaining the safe yield would just cause the reservoir to empty provided that the ongoing drought is as severe as the design drought. The responsibilities of the manager during drought force him to adopt a more sophisticated strategy in order to protect the well-being of consumers rather than merely trying not to exceed the safe yield. However, his choice of short-term alternatives is usually limited to temporary reductions in water use or losses or utilization of emergency water supplies.

To keep the risk of running out of water at a reasonably low level, the manager will always try to adjust the level of withdrawal to the existing conditions during an ongoing drought, primarily the actual volume in storage. In most cases, the manager will impose increasingly severe water use restrictions keyed to water levels in the reservoir so that the critical level of storage is never reached. In other words, the manager's objective during an actual water shortage is to reduce the level of supply in order to avoid the consequences of more severe cutbacks in water delivery at later stages of the drought.

To provide some guidance for a water manager, it would be necessary to determine the level of potential supply deficit that may arise in result of an ongoing drought. Given that an estimate can be provided, the optimal combination of the short-term alternatives can be found. The optimal strategy would minimize total monetary and non-monetary losses resulting from water deficit. The optimum may be approximated by implementing an economically optimal combination of drought management measures. However, the optimization objective will depend on the economic impact accounting stance. For example, the actions that would minimize the utility expenses on emergency sources and importation of water are not the same as those minimizing the losses of residential or industrial customers in the service area.

The negative economic impacts subject to minimization analysis may include: (1) the cost of obtaining supplemental supply from emergency

sources; (2) the implementation costs of water conservation measures; (3) monetary losses (excluding water bill savings) to water consumers that may result from cutbacks in water delivery; (4) revenue losses (excluding cost savings) to the water utility; and (5) other costs incurred by various user sectors within the service area. At least two alternative accounting formats may be used. One format may represent the losses suffered by local economy which are measured by monetary flows to outside interests. The other format may be constructed so as to consider only those losses which are borne by the water utility regardless of the regional impacts. In general considerations, however, it is reasonable to choose the optimization criterion that represents the minimum cost of coping with water shortage to whomever it may occur while avoiding double counting.

The major deficiency of the above approach stems from the existence of non-monetary impacts associated with the alternative drought management actions. Generally, these non-monetary impacts may include the environmental, political, and other social implications such as water quality degradation, loss of wildlife habitats and fisheries, or the loss of recreation opportunities and aesthetics. It is necessary to insure that the economically optimal drought management actions do not create a number of substantial social, environmental, and political impacts which have not been quantified. These impacts must be examined while evaluating individual drought emergency measures.

Current Capacity Planning Methods and Practices

The distinction between the long-term and short-term aspects of planning for droughts is helpful in developing the framework for the evaluation of short-term drought management alternatives. From the short-term point of view the development of optimum drought management plans can proceed independently of the long-run optimization criteria. Given physical characteristics of a water supply system, and the quantity of available water at the onset of a drought, the level of expected deficit that may result may be determined with sufficient accuracy, and used in identifying the optimum strategy. However, many researchers attempted to define the criteria and procedures for developing an optimum strategy that would satisfy both the short-term and long-term objectives. The remainder of this section discusses the conceptual frameworks for water deficit planning proposed by other authors.

Traditional methods for sizing reservoirs require that the user specify the expected demand at the end of a given design period and an acceptable level of risk. Given such input information reservoir capacity can be determined by the method developed by Rippl in 1883 (Fair et al., 1966). For specified steady demand, the required storage during a period of low flow for the design drought is determined from a mass diagram of historic streamflows at the proposed reservoir site.

Some deficiencies of the Rippl method are overcome in the model proposed by Revelle et al. (1969). This model introduces the concept of a linear operating rule and also takes account of the stochastic nature of reservoir inflows. It was initially formulated as a chance-constrained linear programming problem. Advanced formulations of this model are described in Gundelach and Revelle (1975), Sobel (1975), Loucks and Dorfman

(1975), and Loucks et al. (1981). Another group of models was developed that uses capacity as a discrete variable represented by reservoir units with a preselected scale. These models determine optimal sequences of water supply projects by means of dynamic or integer programming (Haimes, 1977).

The above capacity models are capable of taking into account the uncertainty of demand or supply; however, they do not constitute an improvement in dealing with the reliability of a water supply which must be specified by the user. A possible way of providing some guidelines for the user regarding the acceptable level of risk is to demonstrate the relationship between the cost of increasing the levels of reliability.

This approach to risk management in a sophisticated form is described by Boland et al. (1980) and McGary (1979) as applied for determining the optimum level of supply reliability for the water supply system of the Washington Suburban Sanitary Commission. In arriving at the optimum solution, a range of scenarios for drought contingency plans was examined against long-term water supply projects "...to select the combination yielding the best compromise between, on the demand side, risk and the cost of water use restriction, and on the supply side, the economic, social, and environmental cost of providing increased capacity." (Boland et al., 1980:373). Although the costs of water use restrictions were not evaluated, the alternative demand management plans were given a role as a substitute for the last most expensive increments of water supply capacity.

A similar approach to determining reliability was proposed by Clarke et al. (1980), and illustrated within the case study of the Anglian Water Authority supply system in England. In this approach the concept of safe yield is replaced by the "level of service." The latter increases reliability of the system by introducing an operating strategy that imposes various conservation measures during times of depleted reservoir storage. As a result, the level of risk is related to the probability of the reservoir emptying, once the most severe restriction has been introduced. New additions to supply capacity are realized when the level of service drops to an arbitrarily established "critical level of service" representing the minimum level of supply which is considered acceptable. Although this method does not explicitly consider the cost of water use restrictions it may lead to more efficient utilization of reservoir capacity provided the cost of reductions in demand do not exceed the cost of capacity expansion.

The first study that made an attempt to place a value on reliability was carried out by Russell et al. (1970). It contains one of the best treatments of the problem of optimization in providing adequate urban water supplies with emphasis on drought performance. The authors carried out a detailed investigation of the activities of 39 Massachusetts communities which suffered water supply shortages during the 1966 drought. The analysis was performed using a comprehensive framework of concepts, definitions, and methodologies. The long-term investment model (capacity expansion) was based on balancing expected drought losses as a function of specified adequacy level against the cost of adding increments of safe yield to the water system. The optimal plan for timing and sizes of increments to the system's safe yield was developed for given rate of

growth of demand so that it minimized a total present value of capital costs and a discounted sum of expected annual drought losses within a planning horizon of 60 years.

The framework for analysis set by Russell et al. (1970) was carried on by Young et al. (1972), who developed a procedure for estimating income losses in residential, industrial, commercial and municipal sectors associated with varying degrees of water shortage. Their procedure was intended for estimating needs for supply additions as well as for allocating short supplies during emergency conditions. The optimization criterion proposed involved selecting the reservoir storage for which the sum of cost of storage and risk of shortage is at its minimum. The risk of shortage is defined as a sum of the products of projected values of annual regional losses and their respective probabilities of occurrence. This study represents the most comprehensive practical methodology for optimizing reservoir system design that minimizes the sum of investment costs and expected drought losses. However, the major shortcomings of this technique is utilization of a prespecified level of water demand which has to be satisfied. A failure to satisfy the demand is assumed to result in losses. Another important assumption relates to the decision schedule of a water manager which must be given by specifying the level of service and drought management actions to be undertaken during a crisis situation. A solution to the latter problem has been proposed in the recommendations of the study: "An analysis could be done using existing techniques, such as linear and dynamic programming, to evaluate the optimum procedure a water manager should follow to minimize losses due to a water supply shortage." (Young et al., 1972:2-5).

These planning criteria have been reiterated by Russell (1979) in formulating a planning framework for drought contingency programs. The three broad decisions considered by the author as constituting water deficit planning are (Russell, 1979:212):

1. Deciding on levels of expected annual deficits (hence, expected annual losses) in the long run by balancing the costs of alternative system investment paths against the implied expected damages from drought...;

2. Deciding when in the course of a particular period of rainfall shortage to introduce water use restriction (or other water conserving measures) and thus to <u>create</u> a water shortage for consumers. A symmetric decision must, of course, be made about removing any measures once imposed.

3. Deciding on the actual measures which will be taken to reduce water use below normal demand by various amounts.

While the first decision sets out the optimization criterion for the long run, the two remaining decisions are directly related to short-term drought management strategies. The second decision involves "balancing chosen, and therefore certain, damages in the near term against unknown and uncertain--but possibly much larger--damages later in the period." (Russell, 1979:214). Finally, the third decision utilizes the criterion for choosing among alternative conservation programs by finding "the

packages of restrictions designed to achieve particular levels of use reduction...chosen so as to minimize the sum of the resulting losses and costs of implementation: publicity, monitoring, prosecution of offenders and so forth." (Russell, 1979:214).

The criteria set forth by Russell (1979), documented here in the extensive previous quotations, provide a framework for the development of a planning method described in the last sections of this chapter.

Past Drought Emergency Programs

It is useful to contrast the theoretical rules of planning for water deficits with the actual drought emergency programs which had been implemented during water shortage situations in the past. The purpose of this section is to provide the documentation of the literature sources reporting on past drought emergency programs in the U.S. Although the droughts of 1952-1956, 1962-1966, 1976-1977, and 1980-1981 had a significant impact on many water supply systems throughout the country, the most publicized are the experiences of water utilities in California during the 1976-1977 drought.

Table 1 lists 17 publications which describe the experiences of various communities and water districts during the three most recent droughts. The actions undertaken by various systems to avert water shortage indicate that in many cases new or emergency water supply sources were sought in order to increase available supply. Also, most systems utilized more than one drought management measure. Although many drought management programs were quite sophisticated, each of the them were of an ad hoc nature. The measures introduced to conserve dwindling water supplies were selected based on logic, experience and a sense of values rather than the known monetary and non-monetary impacts that they have on water users and the community itself. The following section attempts to formulate a practical procedure for evaluation of various actions that can mimimize the negative impacts of drought on urban areas.

Other experiences can be found in the literature sources listed at the end of this report.

Formulation of a Planning Model

The search for various concepts, procedures, and measurement techniques that are indispensible in planning for water shortages, undertaken in this study, was preceded by the development of a general planning model for the evaluation of individual drought emergency measures and their integration into drought contingency plans. This model, tentatively referred to as drought optimization procedures (DROPS) is designed to determine the minimum-cost short-term drought management programs.

The minimum-cost short-term strategy is built on the assumption that for a given level of water supply deficit (calculated as a difference between predicted supply and forecasted demand), there exists an optimal trade-off between (1) reducing water use by implementing various demand and

TABLE 1

LITERATURE REPORTS ON PAST DROUGHT MANAGEMENT PROGRAMS

Source	Community(s)/ Water District(s)	Year(s)	Reported Drought Management Actions	Other Information
193	York, Pennsylvania	1966	Voluntary restrictions; ban on the use of water hoses; ban on car washing, use of water-cooled air conditioners, filling of swimming pools, serving water in restaurants; customer education,26 water imports by tracks.	Methodology for estimating economic losses from water shortage including computer simulation program
92	New York	1961-1965	Water use restrictions, acquiring emergency supplies.	Political aspects
5	City of Powtucket Water District, Rhode Island	1965-1966	Voluntary conservation, ban on nonessential uses, ban on use of water for air-conditioning	Conservation effectiveness
73	New York water system	1965	Restrictions on outside use, mass media appeals	Effectiveness estimates

TABLE 1 (Continued)

LITERATURE REPORTS ON PAST DROUGHT MANAGEMENT PROGRAMS

Source	Community(s)/ Water District(s)	Year(s)	Reported Drought Management Actions	Other Information
157	48 Massachusetts communities	1962-1966	Restrictions, price adjustment, meter adjustment, leak survey/repairs, provision of emergency supplies, new sources, improvements in present supply, cloud seeding.	Comprehensive analysis of all aspects of water supply in relation to drought, including determination of losses
16	30 districts and communities in 9 California counties	1976	Metering, conservation education, retrofit kits, water recycling, plumbing code changes, restricted outside use, warnings and citations, service shutoffs, rationing, water rate surcharge, prohibitions on new connections, other.	Time series data from over 50 districts on water use and conservation activities
122	35 major urban areas in California (MMWD, EBMUD)	1976-1977	Voluntary and mandatory restrictions, public awareness programs, use of reclaimed water for irrigation, temporary pipeline	Overview of drought-related activities of DWR

TABLE 1 (Continued)

LITERATURE REPORTS ON PAST DROUGHT MANAGEMENT PROGRAMS

Source	Community(s)/ Water District(s)	Year(s)	Reported Drought Management Actions	Other Information
141	NMCWD in California + 11 other utilities	1976-1977	Various types of rationing programs	Cumulative savings in water use
91	8 San Francisco Bay Area utilities: SFWD, EBMUD, CCCWD, MMWD and others	1976-1977	Emergency surface supplies, dead storage, new wells, leak detection, interdistrict transfers, cross-purpose diversions, voluntary and mandatory restrictions	Data on demand reduction and supply augmentation costs to the districts
72	Metropolitan Water District of Southern California	1976-1977	Voluntary conservation, educational program, a rate surcharge, mandatory rationing	Effectiveness of conservation programs
80	FMBUD district in California	1976-1977	Rationing plan, prohibitions against wasteful usage, rate increase, excess use change, educational campaign, new supply source, leak detection and repair.	--

TABLE 1 (Continued)

LITERATURE REPORTS ON PAST DROUGHT MANAGEMENT PROGRAMS

Source	Community(s)/ Water District(s)	Year(s)	Reported Drought Management Actions	Other Information
186	25 municipalities in Illinois	1976-1977	Voluntary restrictions, ban on outdoor usage, rationed industrial/commercial use, rate adjustment, rationing to residential users.	Questionnaire survey data
94	62 towns in Colorado	1976-1978	Obtained short-term surface water sources, trucked in water, changed points of diversion, cleaned out and repaired water mains, restrictions: alternate day sprinkling, sprinkling bans, prohibition of outdoor uses; rationing, raised water rates.	Documentation and analysis of drought responses (questionnaire survey)
72	12 Iowa communities	1977	Mandatory and voluntary restrictions	Results of personal interviews with policy-makers

TABLE 1 (Continued)

LITERATURE REPORTS ON PAST DROUGHT MANAGEMENT PROGRAMS

Source	Community(s)/ Water District(s)	Year(s)	Reported Drought Management Actions	Other Information
146	Hackensack W.C. City of Newark	1980	2.5-mile overland pipeline, and other emergency supply sources	Cost of temporary facilities, lead time
123	Denver Water Dept. Colorado	1977	Tap allocation (new connections), public information program on water conservation	Conservation effectiveness, revenue losses
153	24 Missouri water suppliers	1980	Voluntary conservation, mandatory bans on nonessential uses.	Survey data
42	8 communities in Illinois	1980-1981	Voluntary and mandatory restrictions, new water sources, rate adjustment.	Expenses on drought management measures

loss reduction programs; and (2) acquiring additional water from emergency sources. This optimal trade-off assures that the water supply deficit is met at the minimum total cost.

The foregoing assumption is based on the following three important observations which are associated with the preparation of emergency plans:

1. It is likely that the same percent reduction of water use can be achieved by various means at different total cost.

2. The costs associated with "saving water" may be different than the cost of the same quantity of water obtained from emergency sources.

3. It is not likely that one emergency program can be optimal for all future droughts, therefore, the "best package" of various drought emergency measures will be different depending on the magnitude of water deficit that is to be coped with.

To consider all these specific aspects of water deficit planning, the general model for the development and implementation of optimal shortage mitigation plans is comprised of the following four major elements:

(1) formulation of alternative drought management measures including emergency water supplies;

(2) determination of the magnitude and probability of possible water supply deficits for an existing system capacity;

(3) selection of the "best package" of shortage mitigation measures for water deficits varying in magnitude;

(4) implementation of appropriate drought management plans during a water shortage situation, and

(5) assessment of the effectiveness of alternative capacity expansion paths in terms of investment cost needed to reduce the expected cost of short-term management actions by a unit amount.

The sections which follow focus on the above elements of the general planning model.

Formulation of alternative emergency measures.

Figure 2 displays the various elements that comprise the process of formulating the alternative deficient management alternatives. The three major stages of the process are: (1) identification of possible measures; (2) evaluation of individual measures; and (3) final formulation of feasible alternatives. The purpose of the evaluation of individual demand and loss reduction measures is to prepare an array of applicable, technically feasible and socially acceptable conservation practices together with the information on quantities of water saved and total direct and indirect economic costs associated with each measure. One or more measures assembled into packages for simultaneous implementation are

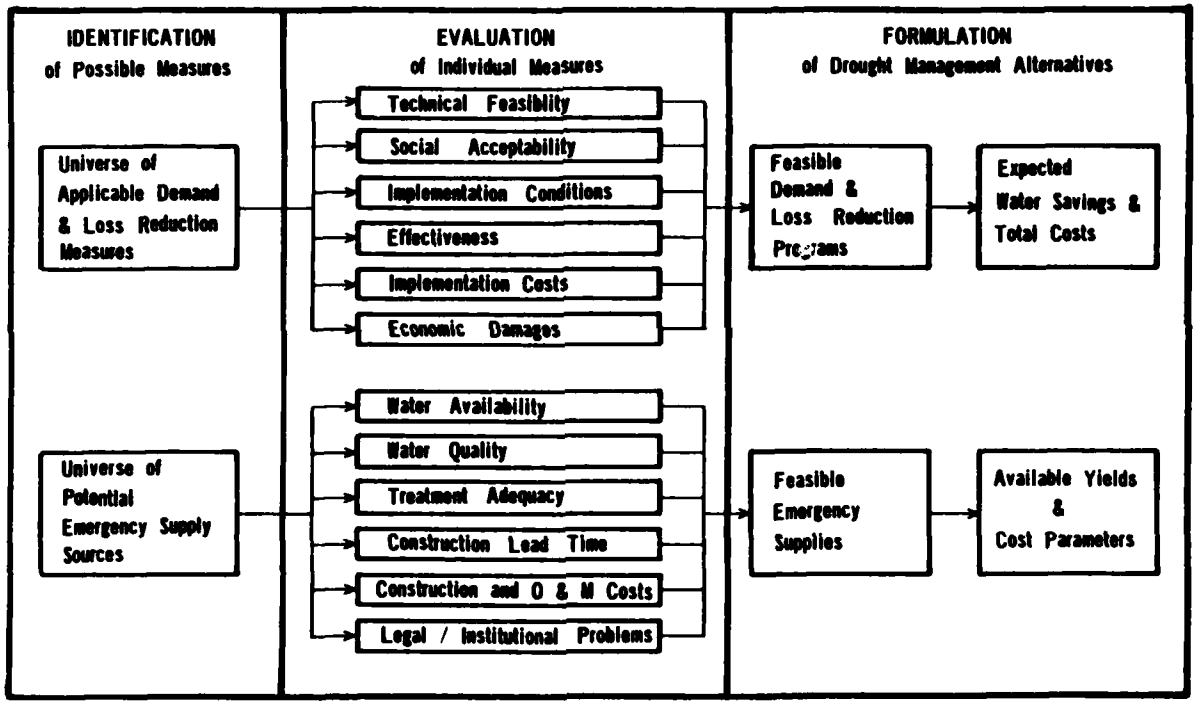

Figure 2. Formulation of Drought Management Alternatives

referred to as demand and loss reduction programs.

The effectiveness is defined as the reduction in water use that can be attributed to the implementation of a specific program. The formula for calculating total quantity of water saved attributed to the implementation of an individual measure j of the program is:

$$E_{jt} = \sum_{k=1}^{s} E_{jkt} \qquad (1)$$

where

$E_{jkt} = Q_{kt} * R_{jkt} * C_{jkt}$ = effectiveness of demand reduction measure j for use sector k, during deficit planning period t (million gallons);

E_{jt} = effectiveness of demand reduction measure j during deficit planning period t summed over all use sectors k = 1,...,s (million gallons);

Q_{kt} = predicted unrestricted use in sector k during planning period t, (million gallons);

R_{jkt} = fraction reduction in use in sector k, during planning period t, expected as a result of implementing measure j;

C_{jkt} = coverage of measure j in use sector k, during planning period t;

Both R_{jkt} and C_{jkt} are fractions, defined on the interval [0,1]. Use sectors are defined as needed for the evaluation of economic losses resulting from reductions in water delivery and the different fraction reductions expected for various use categories. For most practical purposes, the following use categories should be included: (1) residential indoor use, (2) residential outdoor use; (3) industrial by locally owned firms; (4) industrial by externally owned firms; (5) commercial/institutional; and (6) public/unaccounted for.

In the course of formulating water conservation programs, effectiveness is estimated for each measure. Next, all measures comprising a program are investigated for possible interactions in order to make necessary adjustments in the total effectiveness of the program. If a program represents a combination of interactive measures, the effectiveness of the program i can be calculated as:

$$E_i = I_{1/2,3}E_1 + I_{2/1,3}E_2 + I_{3/1,2}E_3 \qquad (2)$$

where:

E_i = effectiveness of water conservation program i, i.e. total volume of water saved by implementing the program i, during drought planning period t, million gallons;

E_1 = effectiveness of measure No. 1, (E_{jt});

$I_{1/2,3}$ = interaction factor or the fraction of the full effectiveness of measure No. 1 given that measure No. 2 and 3 are present in the same conservation program i.

The total cost of each alternative water conservation program is comprised of the cost of implementation (usually borne by the water utility) and monetary losses resulting from cutbacks in water delivery (usually borne by the customers in various sectors). The latter cost arises when an affected customer cannot fully realize his economic benefits due to the curtailment in water use. The overall purpose of the analysis is to determine separate shortage-loss relationships for those user categories which may be affected by water conservation programs. Given sectoral loss curves, the monetary losses associated with any water conservation program are determined based on the effectiveness of that program in each sector.

The identification and evaluation of emergency water supply sources follows similar major steps as those for the evaluation of demand and loss reduction measures. However the information sought is of different character and it includes:

(1) the available quantity and quality of water in potential emergency sources;

(2) the adequacy of existing treatment facilities to produce finished water of acceptable quality when emergency supplies make up some fraction of raw water supply;

(3) the lead time required to construct necessary water transmission and pre-treatment facilities if required;

(4) the construction and operation-maintenance costs required to bring emergency sources on line;

(5) the potential legal and institutional considerations involving permits, rights to the source, or easements for transferal systems; and

(6) the foregone benefits associated with cross-purpose diversions of water from alternative uses.

Formulation of alternative shortage mitigation plans.

The descriptive data on individual shortage mitigation measures discussed in previous sections must be integrated so that optimum plans can be identified. Major steps involved in the development of minimum-cost shortage mitigation plans for specific water supply systems are displayed in Figure 3. A range of probable deficits of various magnitudes and probabilities of occurrence is determined for an existing system, for example, by comparing the current rate of withdrawal to historical drought records of specified duration. Since it is not likely that one emergency program can be optimal for all shortage-causing events, separate plans are developed to match various volumes of possible deficits.

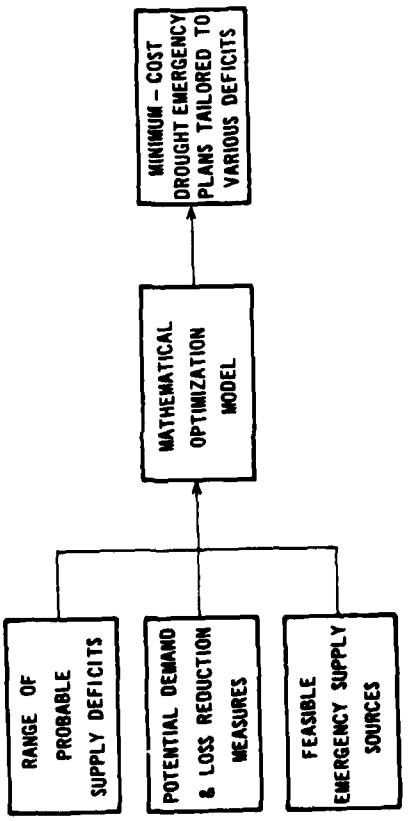

Figure 3. Flow Diagram for Developing Drought Management Plans

A mathematical optimization model of mixed integer programming is applied in order to select the optimal mixes of shortage mitigation measures for each volume of deficit. This procedure solves for both integer and continuous variables, or "activity levels," in the objective function so that the total cost of the emergency program is minimized while meeting constraints on water availability and satisfying the reduced demands. The integer variables allow for the "implement/do not implement" option with regards to alternative water conservation programs, which reflects the actual planning situation. The objective function of the model includes cost terms which may be alternately defined for different accounting formats. The three cost terms are (1) total cost of water conservation programs; (2) cost of water obtained from emergency sources; and (3) cost of water from a primary source. In mathematical notation, the optimization model can be written

$$\underline{\text{Minimize}} \quad \sum_{i=1}^{m} L_i X_i + \sum_{j=1}^{m} C_j Y_j + C_r P_r \tag{3}$$

Subject to:

1. Unrestricted demand constraints:

$$\sum_{i=1}^{m} X_i E_i + \sum_{j=1}^{m} Y_j + P_r \geq U_t \tag{4}$$

2. Unexpected water supply availability in primary sources constraints:

$$P_r \leq U_t = D_p \tag{5}$$

3. Water quality constraints (K = 1,...,1):

$$((S_{rk} P_r + \sum_{j=1}^{m} S_{jk} Y_j)/(P_r + \sum_{j=1}^{m} Y_j)) - \frac{S_k^*}{1-\beta_k} \tag{6}$$

or

$$P_r \left(S_{rk} - \frac{S_k^*}{1-\beta}\right) + \sum_{j=1}^{m} S_{jk} Y_j - \frac{S_k^*}{1-\beta_k} \sum_{j=1}^{s} Y_j - 0 \tag{7}$$

4. Maximum demand reduction constraint:

$$\sum_{i=1}^{n} X_i E_i \leq (1-a)\, U_t \tag{8}$$

5. Water availability in emergency source constraints:

$$Y_j \leq Y_j^* \text{ for } j=1,\ldots,m \tag{9}$$

6. Number of water conservation programs constraints:

$$\sum_{i=1}^{n} X_i = 1 \tag{10}$$

7. Other applicable constraints.

Where:

X_i = logical decision variable representing water conservation programs (i.e., one or more conservation measures that are to be implemented together), $X_i = 1$ when program i is selected, $X_i = 0$ otherwise;

Y_j = volume of water from emergency source j during deficit planning period 5, million gallons;

P_r = total volume of water withdrawn from a primary source (reservoir) during deficit planning period 5, million gallons;

L_i = total cost associated with the implementation of conservation program i (including damages);

C_j = total unit cost of water obtained from emergency source j;

C_r = total unit cost of water obtained from a primary source (non-restrictively low value);

E_i = total volume of water saved by implementing water conservation program i (adjusted for interactions), million gallons:

U_t = unrestricted water use during deficit planning period t, million gallons;

D_p = expected total volume of supply deficit for given probability of occurrence during deficit planning period t; million gallons;

S_{rk} = concentration of quality parameter k in the primary source;

S_{jk} = concentration of quality parameter k in emergency source j;

S_k^* = maximum permissible concentration of quality parameter k in finished water;

β_k = treatment effectiveness in reducing quality parameter k, $\beta_k = (S_{ik} - S_{ek})/S_{ik}$; where S_i = influent concentration, S_{ek} = effluent concentration;

a = arbitrarily established proportion of unrestricted water demand that must be met;

Y_j^* = maximum available volume of water in emergency source j, million gallons.

The constraints specified in Equations 4, 5, 9 and 10 are essential in obtaining a feasible solution. The constraint in Equation 4 assures that unrestricted water demand U_t is balanced with available supply from all sources and water savings. Equation 5 sets a limit on the volume of reservoir withdrawal, while Equation 9 limits the maximum volume of water that can be obtained from emergency sources. The last constraint,

specified in Equation 10, permits only one of n conservation programs to be included into the final solution.

The selection of an appropriate emergency program for implementation during an actual water crisis follows the steps outlined in Figure 4. Preliminary actions of a water manager are contingent upon some indication of potential water shortage. When a shortage alert is in effect, an assessment of the likelihood of water supply deficiency is performed. Having estimated the probable levels of supply in the short-term, a probabilistic forecast of supply deficits is developed by comparing the supply forecasts to short-term forecasts of unrestricted water demand. The unrestricted demand during a shortage situation may be different in comparison with "normal" conditions. In cases where the shortage is caused by drought, the models for predicting unrestricted demand for specific service areas are determined from historical data on water use and weather conditions. Both supply and demand forecasts are expressed in a probabilistic manner by specifying means and confidence intervals to facilitate determination of the probability distribution of predicted water deficits. Provided with a cumulative probability distribution of water deficits, a water manager chooses a volume of deficit with a "sufficiently" low probability of occurrence and matches it with the corresponding optimal drought management plan defined during the preparation stage. If after the implementation of the selected plan it becomes apparent that the volume of deficit will be different than predicted, the appropriate adjustments are made based on revised estimates of the supply deficit (Figure 4).

Evaluation of system investment strategies and long-term water conservation.

The process of formulating drought contingency plans should also be evaluated from the long-run perspective of planning for water supply capacity. The need for expanding supply capacity or for implementing long-term water conservation programs should be assessed in conjunction with drought contingency plans. The problem of finding the best "mix" of new additions to supply capacity, water conservation, and drought management may be reduced to the determination of the benefits of increased system reliability. Figure 5 outlines a procedure for evaluating alternative water supply or water supply/conservation plans from the perspective of reduced costs of coping with recurrent water shortages caused by droughts during a prescribed planning period.

The minimum-cost shortage mitigation plans may be used to determine the expected annual costs of probable deficits in each year of a planning period. For an existing capacity of a water supply system the range of possible supply deficits in each future year is determined by comparing system yields with water use forecasts. A set of various volumes of deficit, each corresponding to the probability of, say, 0.20; 0.10; 0.05; 0.02; and 0.01, can be defined for each year. A mimimum-cost emergency plan for coping with each deficit is determined by means of the optimization procedure, this producing a set of cost estimates. Each estimate is assigned a probability of occurrence, so that higher costs associated with large volumes of deficit have lower probability.

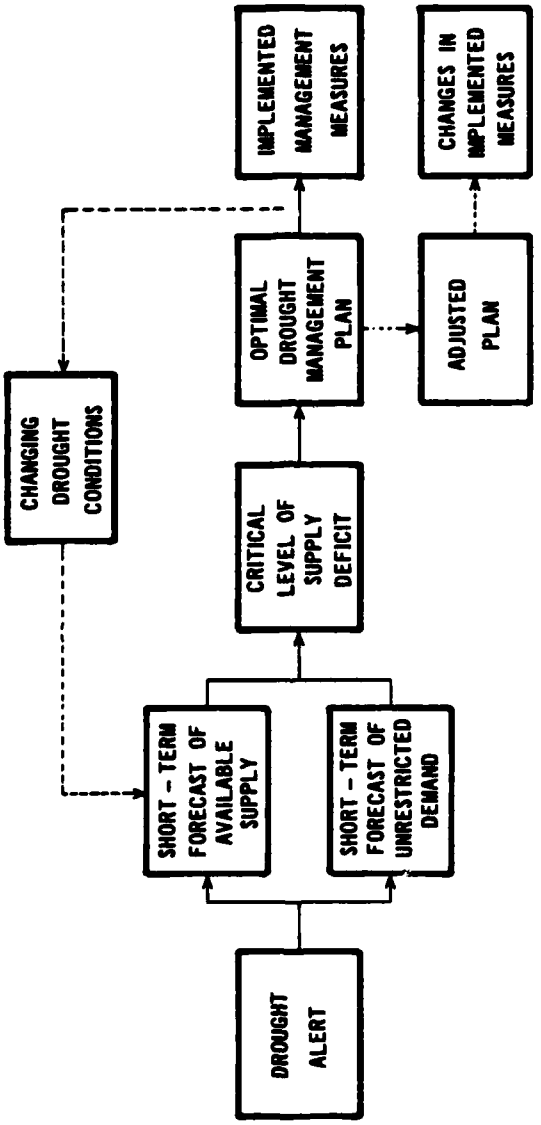

Figure 4. Flow Diagram of Drought Emergency Decisions

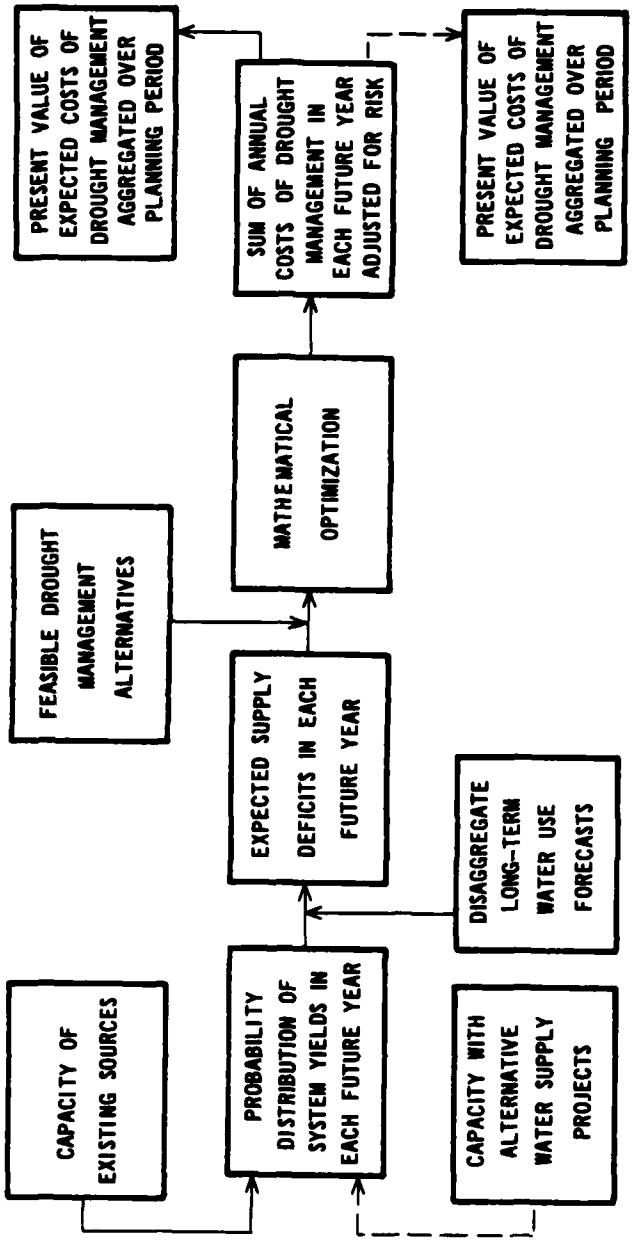

Figure 5. Flow Diagram for Evaluation of Long-Term Alternatives

The critical step of the analysis is the accumulation of the costs of various deficits to determine the total cost for the given year. Theoretically, the accumulated cost can be determined by integrating the cumulative probability distribution curve over the probability interval spanning from, for example, 0.01 to 0.20. The results of integration can be approximated by summing the products of the costs and their respective probabilities according to the formula:

$$EC_t = \sum_{i=1}^{n} p_i C_i \qquad (11)$$

where EC_t = expected cumulative cost of shortage mitigation programs in the future year t adjusted for risk; p_i = probability of occurrence of the i-th supply deficit; C_i = the cost of the optimum emergency plan necessary to avert the i-th deficit, and n = number of probability levels considered. For a specified planning period, the annual expected costs may be reduced to a single number by finding the sum of the present worth of the total cost in each future year. Additions to the source capacity, or long-term water conservation programs, will change the probability distribution of system yields or long-term water use forecasts. For the new set of various volumes of deficit for each future year, the sum of the present worth of yearly shortage mitigation costs is determined by following the procedure outlined above. By comparing the aggregated present worth estimates, the effectiveness of each alternative capacity expansion path is expressed in terms of the investment cost or long-term water conservation programs which are needed to reduce the expected cost of shortage mitigation by a unit amount.

CHAPTER II

EVALUATING THE RISK OF WATER SUPPLY SHORTAGE

Water Supply Forecasting and Drought Alert Procedures

In order to determine the magnitude of supply deficit it is necessary to have well quantified information on climatologic or engineering indicators to signal the onset of a drought and to estimate the risk of supply shortage at each point of an actual drought event. In order to invoke a drought emergency plan, a water supply manager has to rely on a predetermined drought alert procedure. Most often such procedures are based on an arbitrarily established symptom of the water supply system, such as the level of water in a reservoir, a river stage, or the depth of water in wells. Although it is very easy to monitor, these indicators are not capable of providing an early alert. On the other hand, these indicators may reduce the number of false alarms that result in premature implementation of drought management actions, thus imposing unnecessary costs on the system.

Possible improvement in this matter may be accomplished by providing a probabilistic forecast of potential drought conditions related to public water supplies in a larger region, such as statewide. Once the regional drought is recognized, those systems that are vulnerable to a drought related water shortage may carry out a more detailed analysis of the risk of water supply shortage in their sources. Basically, the important question to a water manager is whether the existing reserves of water will be sufficient to support the system throughout the drought. In order to answer this question it is necessary to determine the magnitude of the expected supply deficit. Several techniques which are capable of producing such estimates are summarized in Table 2 and discussed in greater detail in the following sections.

Basic Climatic Index Method

Drought indices provide an indirect measure of relative availability of water. They are derived from comparisons of water requirements, as measured by evaporation and evapotranspiration, to water supplies, as measured by precipitation. The best known of the various indices is the Palmer Drought Index. This is a measure of the moisture stress placed on plants. During normal weather it assumes a value of zero while drought conditions are characterized by negative numbers. Since the Palmer Index is derived through a series of time-consuming calculations, a simpler measurement of water availability is often used. One of such measures called Basin Climatic Index (BCI), was applied to develop drought alert procedures for Kansas (Lampe, 1982).

The BCI is calculated from the following formula:

$$BCI_m = 115 \sum_{i=1}^{m} \left(T_i - \frac{P_i}{10}\right)^{1.11} \qquad (12)$$

TABLE 2

METHODS FOR FORECASTING THE AVAILABILITY OF WATER SUPPLY

Name of the Procedure	Products	Required Input Data	Source
1. Basin Climatic Index (BCI) Method	Expected total 12 months' runoff with 10, 25, and 50 percent probability of occurrence	Drainage basin or regional data: long-term average BCI's and runoff, monthly precipitation and temperature	109
2. Position Analysis	Percent probability of complete exhaustion of the reservoir storage during drought	Monthly inflow, withdrawals and evaporation for a reservoir plus current reservoir storage	165
3. USGS Techniques	Percent probability of a dry reservoir based on a representative trace of inflows	Historical and filled in streamflow data	89, 165
4. National Weather Service River Forecasting Systems (NWS RFS)	Simulated streamflows, total volume of flow, maximum, minimum and average mean daily flow	Hydrological parameters and initial conditions of a watershed including moisture storage contents, snow pack water-equivalents, future time series of mean areal precipitation and temperature (at least 10-20 years of record)	127, 97, 64, 65, 4, 132, 149, 170, 128, 180, 47
4.1 Snow Accumulation and Ablation Model	Snow cover outflow plus rain that fell on bare ground	Air temperature, snow pack water equivalents, other snow cover variables	4
4.2 Sacramento Soil Moisture Accounting Model	Five components of water flow: (1) direct runoff; (2) surface runoff; (3) lateral drainage interflow; (4) supplementary baseflow; (5) primary baseflow	As for the NWS RFS model	33, 149

TABLE 2 (Continued)

METHODS FOR FORECASTING THE AVAILABILITY OF WATER SUPPLY

Name of the Procedure	Products	Required Input Data	Source
4.3 Sensitivity Approach (for the NWS RFS rainfall-runoff procedures)	As for the NWS RFS model	Typical trace of 6-hour interval rain data, current soil moisture, variance of rainfall input	192
4.4 Stochastic Conceptual Hydrologic Model (based on NWS RFS system)	Streamflow forecasts 6, 12, 18, 24, 30, and 36 hours in advance	Rainfall data in 6-hour time steps and incoming real time discharge	104

where subscript m denotes the length of the period in months for which the index is calculated. P_i and T_i are, respectively, monthly precipitation in inches and monthly temperature in degrees Fahrenheit in month i of the m-month period. The period used in Kansas was 12 months, although 6- or 24-month periods were proposed to be examined in the search of the length of lead time that is best correlated with extremely low water supply conditions for other regions of the country.

The rationale for applying the 12-month running BCI's to predict relative availability of water for public water supplies is based on the dependence of supply sources on runoff, the magnitude of which can be related to the BCI. Lampe (1982) demonstrates the use of 12-month moving average BCI to predict the probability of various degrees of drought twelve months into the future. The prediction procedure utilized a relationship between predicted volumes of runoff during a 12 month period in the future and the 12-month moving average BCI for the last month. The forecast was made in terms of the probability of having less than a certain amount of runoff during the upcoming 12 months. The authors developed a series of curves which show the projected 12 month normalized runoff (expressed as a ratio of expected runoff to the long-term average runoff) in relation to the values of preceding 12 month BCI. Separate curves were developed for 10, 25, and 50 percent probability of occurrence for the nine climatological regions of Kansas.

The relative simplicity of the BCI method justifies its application as the first resort technique for assessing the likelihood of storage deficiencies for systems that rely on reservoir supplies. The statewide application of this procedure requires that long-term average BCI's are determined for various regions of a state and small water supply systems can use the forecasted runoff to assess their vulnerability to water shortage. Large water supply systems can perform all evaluations for the watersheds of their sources, thus improving the accuracy of the estimates.

"Position Analysis" and USGS Techniques

Sheer (1980) described a simple analysis of the availability of water in the Occoquan Reservoir during the 1977 drought. His calculations assessed the risk of the reservoir having gone dry dependent upon the current reservoir storage and soil moisture of the supply system. This simulation, called the "position analysis," was designed to determine in how many years in the historical record the reservoir would have gone dry if the demands had been as high as they were in 1977, and the reservoir as low as it was in 1977. For each year the current storage was added to the inflows for next month, and the expected water use and allowance for evaporation in that month were subtracted. The calculation was then repeated for each subsequent month for each period of the historical record under consideration. The results were expressed in terms of the risk of a dry reservoir measured as a ratio of years when the reservoir would have been empty over the number of years of record. The author recommended this approach as the technique of first resort in estimating the risk of streamflow induced drought.

More refined "position analysis" has been performed by the USGS staff based upon historical and "filled in" streamflow data for a net period of

49 years in order to find a representative trace of inflows to the Occoquan Reservoir which can be expected to occur in any given year. Twenty-seven years were removed from the 49-year record since they were judged as dissimilar to the year 1977. The remaining 22 years of record were used to determine in how many years in the historical record the reservoir would have gone dry given the demands and the reservoir storage as existed in September 1977. This analysis is described by Sheer (1980), while the full presentation of the USGS techniques can be found in Hirsch (1978).

NWS Extended Streamflow Prediction Techniques

The National Weather Service (NWS) has developed a computerized system of hydrologic forecast procedures which are referred to as the NWS ESP method (National Weather Service Extended Streamflow Prediction) or NWS RFS (National Weather Service River Forecasting Systems) throughout the literature. The NWS RFS system is comprised of several hydrologic forecast procedures including data acquisition and processing, computation of mean areal precipitation (MAP) in a watershed, snow accumulation and ablation, soil moisture accounting, parameter optimization and verification, and operational forecasting. All these procedures are described in several technical memoranda of the National Oceanic and Atmospheric Administration or NOAA (Monro, 1971; Hydrologic Research Laboratory Staff, 1972; Fread, 1973, 1974; Anderson, 1973; Morris, 1975; and Peck, 1976). Overviews of the NWS RFS system at various stages of development are given by Sitter (1973), Monro and Anderson (1974), Twedt, Schaake and Peck (1977), and Curtis and Schaake (1979).

The soil moisture accounting model, referred to as the Sacramento model, has been developed by the California River Forecast Center and is described by Burnash et al. (1973) and by Peck (1976). The model distinguishes two soil moisture zones: (1) the upper zone representing the upper soil layer with interception storage, and (2) the lower zone representing the bulk of the soil moisture and groundwater storage. Two forms of water are distinguished in each zone, "tension water" and "free water", the former being depleted only by evapotransporation. The flow rate of water from the upper zone to the lower zone is a function of water content in the two zones. Generally, the model is deterministic with lumped input and lumped parameter, and is capable of generating five components of water flow which are converted to a discharge hydrograph at a 6-hour time step for a given volume of moisture input over that period.

The moisture input to the model also can be determined using a snow accumulation and ablation subroutine described by Anderson (1973). This auxiliary model utilizes air temperature as the only index to energy exchange across the air-snow boundary.

The NWS RFS technique can be used to produce probablistic streamflows during designated time periods. The simulated streamflows serve as artificial flow records to determine total volume of flow, maximum mean daily flow, minimum mean daily flow, average mean daily flow and other statistical characteristics. The input data must include: (1) a set of hydrological parameters of a basin under consideration; (2) initial basin conditions that represent the current state of the catchment in terms of moisture storage in the soil, snow pack water-equivalents, and other snow

cover variables, and (3) representative future time series of mean and precipitation and temperature (at least 10-20 years of historical record).

An application of the NWS RFS procedures to produce the estimates of the risk of water supply shortage during the 1977 depletion of the Occoquan Reservoir have been described by Sheer (1980). Young et al. (1980) developed an alternative procedure to the NWS RFS streamflow simulation to determine the expected yield and standard deviation yield for a given catchment. The authors proposed a sensitivity analysis of the rainfall-runoff models used by the NWS. Instead of performing an extensive simulation of equally likely rainfall traces, the sensitivity approach uses only one typical trace of 6-hour interval rainfall data, current soil moisture estimates and variance of the rainfall input. The sensitivity analysis requires less computer time than the NWS procedure.

Finally, Kitandis and Bras (1980a, 1980b) reformulated the nonlinear conceptual rainfall-runoff model used by the NWS RFS into a form amenable to the analysis of uncertainty and to real-time forecasting of river discharges within a stochastic process framework. The model developed by the authors is capable of processing incoming real-time discharge and rainfall information in 6-hour time steps to produce streamflow forecasts 6, 12, 18, 24, 30, and 36 hours in advance. These lead-time periods are comparable to the response time of a catchment. The mathematically rigorous approach proposed by the authors may offer a substantial improvement in water supply forecasting where more precise weather forecasts or historical rainfall information are available.

Forecasting Unrestricted Water Demand During Drought

Techniques for predicting short-term municipal and industrial water demands are complementary to the procedures for determining expected "inflows" during a drought period. The unrestricted demand determined on a weekly or monthly basis is necessary to assess the magnitude of expected supply deficit. The latter constitutes a basis for selecting the optimum drought management strategy. Municipal water consumption during drought may be higher in comparison with "normal" weather use due to increased lawn sprinkling.

In addition to total municipal demand, short-term disaggregate water-use forecasts may be required to evaluate the effectiveness of water conservation measures. Since such water conservation measures affect different classes of water use in different ways, their effectiveness cannot be determined from aggregate data. Also, the estimates of drought damages are prepared for specific categories of customers.

Several models that can be used to determine the effects of drought on the level of water consumption have been compiled from published literature and listed in Table 3. All of them include one or more weather-related variables as predictors. Unfortunately, the number of use categories is very limited, and includes municipal, total residential, and sprinkling uses. Four models presented in Table 3 address monthly water consumption and three use annual demand as the dependent variable. Although direct application of these models for individual municipalities may yield considerable errors, a significant improvement can be achieved by

TABLE 3

METHODS FOR FORECASTING WATER DEMAND DURING DROUGHT

No.	Dependent Variable Units	Model, Statistics, Sample Description	Explanatory Variables	Source
1	P_t, gpcd Observed total annual consumption in year t	$P_t = a_t + 3.57\ t - 0.76\ W_t + 0.55\ E_t$	a_t = intercept t = time running from 0 (1950) to 12 (1962) W_t = a weather index for year t calculated as a sum of the Palmer Drought Index over the 4 summer months E_t = an index of industrial employment in the particular community in year t assuming 1950 level of employment = 100	157
2	Q, 1000 cu.ft/yr (quantity of water demanded by household, i.e. per meter)	$Q = 2.49e^{-.1278P}\ Y^{.4619}\ R^{-.1679}\ N^{.4345}$ $R^2 = .545$; F - 63.69 (Deg. of freedom: 4/213) 218 cities included in the 1960 AWWA Survey	P = average water price, $/100 cu ft. Y = median household income, $/yr R = precipitation during the defined growing season, inches N = average number of residents per meter	63

TABLE 3 (Continued)

METHODS FOR FORECASTING WATER DEMAND DURING DROUGHT

No.	Dependent Variable Units	Model, Statistics, Sample Description	Explanatory Variables	Source
3	ln Q_t, gcud (average gallons per connection per day in month t)	$\ln Q_t = -2.615 - .062 \ln X_{1t} + 1.563 \ln X_{2t} - .469 \ln X_{3t} + .672 \ln X_{4t} + 7.259 \ln D$ $R^2 = 0.97$ 1961 to 1974 monthly production records for Salt Lake City	X_{1t} = total rainfall in inches (seasonal: April to October) X_{2t} = average temperature, ^{o}F (seasonal: April to October) X_{3t} = constant price, \$/1000 cu ft. X_{4t} = daylight hours, percent (seasonal: April to October) X_{4t} = nongrowing season dummy variable (November to March)	79
4	Y, gpcd (average municipal use in a summer month excluding industrial and institutional sector)	$Y = -19.0 + 2.9 X_1 - 1.2 X_2 - 14.5 X_3 - 15.0 X_4 - 8.4 X_5 + 8.5 X_6 - 43.4 X_7 - 30.1 X_8 - 24.9 X_9 + 18.6 X_{10} - 19.7 X_{11} + 55.7 X_{12}$ $R^2 = 0.9337$ 8 Iowa communities, four summer months 1976	X_1 = average temperature of a month, deg. X_2 = total precipitation, inches Dummy variables: X_3 = 1 for June, 0 for other months X_4 = 1 for July, 0 for other months X_5 = 1 for Aug., 0 for other months X_6 = 1 for Community A, 0 otherwise X_7 = 1 for Community B, 0 otherwise . . X_{12} = 1 for Community G, 0 otherwise	135

TABLE 3 (Continued)

METHODS FOR FORECASTING WATER DEMAND DURING DROUGHT

No.	Dependent Variable Units	Model, Statistics, Sample Description	Explanatory Variables	Source
5a	GPCD (gpcd) (total urban water consumption for month in question)	$GPCD = -169.33 + 7.92 X_1 - 2.59 X_2 + 4.66 X_3 + 2.15 X_4^1$ $R^2 = 0.800$ San Diego, California; monthly consumption during the period 1960-1975	X_1 = evaporation for month, inches X_2 = days of precipitation exceeding 0.1 inch for month X_4 = mean county income in 1967 dollars X_5 = average temperature for month, deg. F	37
5b		$GPCD = 41.05 + 8.98 X_1 - 1.58 X_2 + 2.35 X_3$ $R^2 = 0.780$ Los Angeles, California; monthly consumption during the period 1960-1975		
6	qs, gal/day/dwelling unit (average summer sprinkling demand for metered residential areas with public sewer in the East)	$Qs = A \cdot 6^{-01793} \frac{(W_s - 0.6r_s)^{2.93}}{P_s^{1.57}} B^{1.45} Y$ $R^2 = 0.927$ 11 master metered residential areas with public sewer in the Eastern U.S.	A = coefficient to fit curve to specific area B = irrigable area per dwelling unit, acres P_s = marginal charge for water, units/100 gal Y = market value of dwelling unit r_s = summer precipitation, inches W_s = summer potential evapotranspiration, inches	95

TABLE 3 (Continued)

METHODS FOR FORECASTING WATER DEMAND DURING DROUGHT

No.	Dependent Variable Units	Model, Statistics, Sample Description	Explanatory Variables	Source
7	LGAL, mgd (logarithm of total 1975 municipal water use in a county)	LGAL = 2.78 + 1.09 (LPOP) + 0.18 (LMM) - 0.59 (LRN) R^2 = 0.917 82 counties in Mississippi	LPOP = logarithm of total population served by all municipal systems in each county LMM = logarithm of industrialization index (ratio of personal income in manufacturing and mining to total nonfarm personal income) LRN = logarithm of annual average rainfall for each county	66
8	Q, 100 cu. ft/mo. (monthly water consumption of average household)	Q = -14.2 - .331 P -1.96 D + .0467 Y + .0147 W R^2 = 0.82 Monthly data from Jan. 1974 to Sept. 1977 for Tucson	P = marginal price facing average household, ¢/100 cu. ft. D = difference = actual water and sewer use bill minus what would have been paid if all water was sold at the marginal rate, dollars Y = personal income per household, dollars per month W = weather variable = evapotranspiration from bermuda grass minus rainfall, inches	18

TABLE 3 (Continued)

METHODS FOR FORECASTING WATER DEMAND DURING DROUGHT

No.	Dependent Variable Units	Model, Statistics, Sample Description	Explanatory Variables	Source
9	Y_r gallons/household/day (total residential water consumption)	$Y_r = -0.350 - 0.018\ X_2 + 0.316\ X_3 + 0.334\ X_4 - 0.272^2 X_5 - 0.740^3 X_6$	X_2 = average daily rainfall during a period, inches X_3 = average temperature per period X_4 = appraised house and lot value of the residential customer X_5 = real water price in cents per 1000 gallons X_6 = household size, persons (all variables in logarithmic forms)	48
	Y_s gal/household/day (residential sprinkling demand)	$Y_s = -26.204 - 0.206\ X_2 + 5.141\ X_3 + 0.363\ X_4 - 138\ X_5^2$		
		261 households in the city of Raleigh observed over 68 time periods of approx. 30 days from May 1969 to December 1974		

performing calibration of a selected model based on local water use statistics. Again, for the purpose of drought contigency planning, the disaggregated time series water use data should be used if available. Where appropriate historical water use data are not available, the selection of an estimated model from Table 3 should be made with caution after consulting the original source. The studies that may be helpful in this task are discussed in greater detail below.

One of the most extensive and reliable cross-sectional studies of residential water demand is described by Howe and Linaweaver (1967). Using data collected by the Residential Water-Use Research Project at The Johns Hopkins University, the authors analyzed 39 master-metered residential areas throughout the United States. For each area the accumulated flow was recorded every fifteen minutes for 2- and 3-year periods during the 1960's and aggregated to hourly, daily, seasonal, and annual figures. Indoor and outdoor uses were separated, with the latter divided into eastern and western regions of the nation. A total of nine demand functions were estimated. Separate linear equations were determined for the domestic demand in three types of residential areas: (1) metered with public sewer, (2) flat rate and apartments with public sewer, and (3) metered areas with septic tanks. Summer sprinkling demand were provided for (1) metered areas with public sewer, west; (2) metered areas with public sewer, east; and (3) flat rate areas with public sewer. For the latter types of areas also maximum day sprinkling demand functions were evaluated. One of the summer sprinkling demand models is presented in Table 3 as No. 6.

More recent studies of residential water demand are described by Foster and Beattie (1979), Billings and Agthe (1980), and Danielson (1979). Since the first study used average annual water use as dependent variable, the usefulness of its results to drought forecasting is only limited. Billings and Agthe (1980) developed a model for monthly water consumption of an average household based on monthly consumption data from January 1974 to September 1977 for Tucson, Arizona. Danielson (1979) developed separate water-demand models for total residential, sprinkling and winter demands based on a sample of 261 households in Raleigh, North Carolina.

Total municipal demand models were presented by Russell et al. (1970), Hansen and Narayanan (1981), Motoko and Warren (1981), California Department of Water Resources (1978) and Frnka (1979). Hansen and Narayanan (1981) proposed a monthly regression model for forecasting water demand useful for predicting the effects of various water conservation measures. Although the model coefficients have been estimated from total municipal water use in Salt Lake City, Utah, it is possible to estimate regression equations for dissaggregated data. Motoko and Warren (1981) proposed a similar monthly regression model developed for eight Iowa communities.

Other categories than municipal and residential categories can be used in disaggregate forecasts. Industrial water use was analyzed by DeRooy (1974), Hansen et al. (1979), Klimek (1972), Rees (1969), and Stevens and Kaltor (1975). Commercial and institutional use categories are treated in Headley (1963), Kim and McCuen (1979), McCuen et al. (1975), Thompson et al. (1976), and Wolff et al. (1966). Other studies dealing with water demand forecasting are documented in Dziegielewski et al. (1981).

CHAPTER III

EVALUATION OF CONTINGENT WATER CONSERVATION MEASURES

Contingent water conservation measures encompass a large and dissimilar group of regulations, devices, practices and programs that can reduce water use when implemented during a drought-induced water crisis. Water conservation programs consist of one or more carefully defined conservation measures. For the purpose of drought management planning, it is necessary to develop the estimates of costs and conservation effectiveness for several alternative water conservation programs. The analysis of individual conservation measures must be undertaken prior to the formulation of conservation programs in order to produce these estimates.

The approach proposed in this study represents a modification of the evaluation procedure developed for evaluation of water conservation within the Corps of Engineers water supply planning. This approach is described in four reports of the U.S. Army Engineer Institute for Water Resources (Baumann et al. 1969, 1980, 1981 and Boland et al. 1982). The Corps of Engineers procedure formulates the optimum combination of supply augmentation and demand reduction alternatives in the long-run water supply plans. The first phase in the formulation of water conservation proposals involves the identification of the characteristics and effects of each individual measure. In the second phase the effects of the conservation measures are analyzed with respect to the characteristics of specific water supply plans.

The evaluation of contingent water conservation measures is carried out in a manner similar to the measure-specific analysis of the Corps of Engineers procedure. The purpose of the evaluation of individual water conservation measures is to prepare an array of applicable, technically feasible, socially acceptable conservation practices together with the information on quantities of water saved and total economic losses associated with each measure. The subsequent steps in the analysis produces a decreasing number of more and more narrowly defined measures by rejecting those measures which are judged infeasible. In this way, the array of the "best" measures is identified in a most efficient way, thus minimizing the analytical effort. An alternative way would be to develop necessary information on effectiveness and costs for all possible conservation measures followed by the selection of the best measures by means of mathematical optimization. The amount of information needed in such an approach would be prohibitive.

The method proposed relies upon the planner's judgement in early planning stages, thus reducing the number of alternatives that have to be evaluated.[1] Although this approach may appear as overly simplified, it is

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[1]The reader should be alerted to the fact that such a judgement must be justified in the documentation of the planning process.

intended to guide a planner in his efforts and to achieve the desired final product as quickly as possible. The following sections describe the subsequent steps that lead to the formulation of alternative conservation programs. At each step, pertinent literature references are briefly summarized to facilitate the analysis.

Determination of Applicable Measures

The purpose of this step is to select a set of water conservation measures that are applicable to the study area during drought emergency situations. The first task is to examine the universe of all possible water conservation measures. Listings of various water conservation measures are indispensable. These can be drawn from Flack (1981), U.S. Environmental Protection Agency (1980), New England River Basin Commission (1980b), Stone (1978), Schaefer (1979), Lattie and Vossbrink (1977), Fletcher and Sharpe (1978), Milne (1976, 1979), and Minton, et al. (1979). In some of the above references, conservation measures are categorized into groups. Flack (1981) distinguishes four broad categories: (1) structural: metering, flow control devices, recycling systems and horticultural changes; (2) operational: leakage detection, water-use restrictions, and pressure reduction; (3) economic: pricing policy, incentives (such as rebates, tax credits, or subsidies), and penalties, and (4) socio-political: public education and laws.

Several potential water conservation measures are presented in Table 4. They are categorized into three major classes according to the originating action, i.e, measures resulting from (1) management actions, (2) regulatory actions, and (3) educational efforts.

While preparing a list of applicable contingent measures it is necessary to check if a given measure meets the following tests:

(1) it addresses water uses which occur within the study area;

(2) it has not been fully implemented as a long-term conservation measure in the area; and

(3) it is rapidly mobilized during a crisis situation.

In order to minimize analytical effort, the measures considered at this point should be defined in relatively general terms; however, their specification should be sufficient to assess the above tests of applicability.

Determination of Technical Feasibility

In this step, all applicable measures are tested for their capability of producing a reduction in water use. Some measures may not result in measurable reduction in quantity of water used during a drought planning period. An example of technical infeasibility may be present in the case of devices for reducing toilet flushing volumes where flushing efficiency is so reduced that double-flushing occurs.

TABLE 4

LIST OF DEMAND AND LOSS REDUCTION MEASURES

1. EDUCATION
   Direct mail:
   pamphlets, leaflets, posters, bill inserts, newsletters, handbooks, buttons, bumper stickers

   News media:
   radio/TV adds and announcements, newspaper articles, movies

   Personal contact:
   speaker programs, slide shows, booths at fairs, customer assistance

   Special events:
   school talks, slogan/poster contests, posters around town, billboards, displays, decals, water served only on request

2. TECHNOLOGY
   Domestic indoor:
   water closet inserts, shower flow-control devices, water conservation kits, reuse recycle systems, faucet flow restrictors

   Domestic outdoor:
   moisture sensors, hose meters, sprinkling timers, swimming pool covers

3. RATIONING
   Mandatory:
   fixed allocation, per capita, per household, prior use, variable percentage plan, inconvenience

   Pricing:
   drought surcharge, seasonal use charge, excess use charge, penalties

4. RESTRICTIONS/BANS
   Domestic indoor/outdoor:
   lawn sprinkling, car washing, pool filling, pavement hosing, air conditioning

   Public/institutional:
   street cleaning, public fountains, landscape irrigation, shortened school day and office hours

   Industrial/commercial:
   car washes, limited time of operation, recycling

TABLE 4 (Continued)

LIST OF DEMAND AND LOSS REDUCTION MEASURES

5. SYSTEM MODIFICATIONS

Raw water source:

evaporation suppression, reduced dam leaks, deapened wells, surged and cleaned wells, surplus water transfers

Treatment plant:

recirculation of washwater, blending impaired quality water

Distribution system:

pressure reduction, leak detection and repair, discontinued hydrant and main flushing

Technical feasibility of a particular conservation measure can be judged on, for example, field tests of water-saving devices. Valuable information on the implementation of home water-saving devices in California can be found in Appendices G and H of A Pilot Water Conservation Program (Johnson, et al., 1978). Milne (1976, 1979) evaluated over 40 commercially available water-saving devices, and discussed the design and installation of small on-site residential water use systems. Needs and methods of conservation by the use of water-saving devices and their impacts on water supply and drainage systems are discussed by Shelton and Soporowski (1976). Additional information on the technical performance of various water conservation measures can be obtained from Bailey, et al. (1969); AWWA (1971); Alderfer (1979); Flack, et al. (1977); Moran (1978); White et al. (1980); and Hancock (1979).

The level of detail in the examination of technical feasibility should be only sufficient to determine whether a measurable reduction in water use will or will not occur. If the answer is positive, then a measure under consideration should be included in the list of technically feasible water conservation measures. If the answer cannot be provided based on this preliminary examination, then the measure in question should be retained for further analysis.

Determination of Social Acceptability

Applicable and technically feasible measures must be evaluated with respect to the probable response of the various sectors of the community. It is important to know which measures may be unacceptable to the public or some sub-groups of the population in the community. A given conservation measure may be adopted by only a certain percentage of all customers, and the estimate of the degree of adoption must be known in order to calculate the effectiveness of each measure.

The most likely responses to specific water conservation measures may be identified from the literature. The reports that provide survey data on adoption of water conservation measures are listed in Table 5. The most comprehensive study of this subject has been performed by Sims et al. (1982). If the literature data are judged insufficient to determine the social acceptability of some measures, then the analysis of acceptability must be undertaken. A method of assessing the social acceptance of conservation measures is described in Procedures Manual (Baumann, et al. 1980). The method uses interviews with persons occupying positions of influence in both public and private institutions, and mail questionnaires with a random sample of the general public. Snodgrass and Hill (1977) proposed a procedure for identifying community acceptance of various conservation measures and tested it in Lafayette and Louisville, Colorado.

The result of this step is a list of still broadly defined measures that are applicable, technically feasible and socially acceptable. At this point more precise definitions of these measures can be developed.

TABLE 5

LITERATURE DATA ON ACCEPTABILITY OF WATER CONSERVATION MEASURES

Conservation Measure	Subjects	Source
Short-term water-use restrictions	Managers and customers of 17 eastern United States water utilities	1
Flow-reduction devices	Plumbers, architects, equipment manufacturers, and houseowners	12
Drought emergency water conservation programs	Sample of 900 consumers served by 9 water agencies in San Francisco Bay Area	30, 31
Domestic water-conserving technology	Home builders and municipal officials in Mississippi	41
Mandatory and voluntary water conservation measures	Personal interviews of 56 policy-makers of 12 Iowa communities	134
Freely distributed 3-part water conservation kits	A sample of 637 households in the City of Oxnard, California	130
Four rationing procedures: percentage reduction of prior use, seasonal allotment per capita, fixed allotment, and total sprinkler ban	North Marin County Water District in California	141
Technological, behavioral, attitudes towards imposed measures	A stratified random sample of 1383 residents from four cities: Aurora (Colorado), Elmhurst (Illinois), Tucson (Arizona), Indianapolis, (Indiana)	167
Legal restrictions, economic measures, landscape irrigation techniques	A sample of residents in Lafayette and Louisville, Colorado	172

TABLE 5 (Continued)

LITERATURE DATA ON ACCEPTABILITY OF
WATER CONSERVATION MEASURES

Conservation Measure	Subjects	Source
Long-term and short-term measures: universal metering, low-flow devices, native vegetations for new landscapes, increasing block pricing, public education, non-drinking reuse, growth restrictions, implementation of restrictions and allotments, and surcharges on prices for metered services.	A sample of 105 customers in each of 7 small towns in Northern Colorado and also water officials	189
Water conservation measures identified by respondents	Consumers in Homestead and Palm Beach, Florida	167

Identification of Potential Water Conservation Measures

Based on the results of the three previous tests, the water conservation measures can be defined more narrowly or subdivided into several constituent parts, each constituting a separate measure. For example, the same water conservation measure may be applied to all water uses, or its specific major water uses such as residential, industrial or commercial. These narrowly defined measures are now called potential water conservation measures.

Some examples of narrowly defined water conservation measures can be found in Morris and Jones (1980) and Minton, et al. (1979). Other examples of specific water conservation measures are given in the Procedures Manual (Baumann et al. 1980). These definitions may be as follows:

(1) "community-wide distribution of water saving kits and information pamphlets aimed at reducing water use by all user classes";

(2) "a sprinkling ordinance requiring homeowners to water their lawns only on alternate days between 8 p.m. and 10 a.m.";

(3) "a televised educational campaign to educate residential customers in the use of water within the home."

The result of this step is a list of potential contingent water conservation measures where each measure is stated in very specific, narrowly defined terms. Further formulation of these measures requires additional information on how these specific measures are to be implemented. These are determined in the next step.

Analysis of Implementation Conditions

The list of measures prepared in the previous step contains the description of what must be done but does not say how to accomplish it. The analysis of implementation conditions focuses on the investigation of the best implementation methods and responsible agencies. It may happen that such investigation will show that institutional arrangements in the study area make implementation of some measures impossible.

The role of individual agencies and companies in implementation of several conservation measures, such as retrofit devices, devices for new construction, regulatory code changes, metering, pricing, leak detection, water reuse, sharing water supplies and public education, was identified in a study sponsored by the U.S. Water Resources Council (1980). Hoffman et al. (1979) described the policy-making process of choosing strategies to cope with drought and assessed administrative feasibility of different drought policies. A conservation suitability criterion was developed by Minton et al. (1980) in their institutional analysis of municipal water supply in Anchorage, Alaska.

In order to evaluate existing implementation conditions, some water conservation measures may be examined for their consistency with existing land use patterns as proposed by Alderfer (1979). Brainard (1979) pointed to the problems which may constrain implementation of a leak detection and

repair program. The information needed for the determination of implementation conditions of other conservation measures was identified by Flack (1981). Additional information may be obtained from Motoko (1981); Johnson et al. (1978), Cartee and Williams (1979), Hancock (1979) and McDonald et al. (1981).

The above references may be useful in determining the roles and responsibilities of private groups, organized interests and individuals within implementation plans for a water conservation program. For example, in the case of legal restrictions on the quantity of water use during drought emergency, a greater variety of agencies, organizations, and individuals will participate in the implementation of this measure than in the case of voluntary measures where the participation of private groups will be more important.

An additional aspect of implementation conditions is coverage of individual measures. It is necessary to define the spatial and sectoral coverage of each measure. These two dimensions define the areal coverage and particular water use classes to which the measure will apply.

After determining the implementation conditions for each measure, the process of formulating individual measures nears completion. These narrowly defined measures, together with the information gained on each measure, will support the analyses of effectiveness, implementation costs and the formulation of contingency conservation programs.

Determination of Effectiveness

The determination of effectiveness is a fundamental part of the analysis of an individual water conservation measure. The effectiveness is the reduction in water use that can be attributed to its implementation, and it is expressed as the average expected changes in rate of use during the period of drought.

The formula used to obtain estimates of effectiveness was specified in Chapter I (Eq. 9 and Eq. 10). According to this formula three quantities must be known in order to find the expected volume of water saved by each measure under consideration. These are:

(1) unrestricted water use in each user sector that will be affected by the measure;

(2) fraction reduction in the use of water in each affected sector expected as a result of implementing the measure; and

(3) coverage of the conservation measure in each affected use sector expressed as a fraction of water use by that sector.

Once these quantities are known, the summary effect (or total effectiveness) of any conservation measure expressed as quantity of water saved per unit time (e.g., gallons per day) is found by summing the volumes of water saved in each of the affected sectors. In addition to the total effectiveness, the volumes of water saved in each sector must be retained for the analysis of possible economic losses that may result from cutbacks

in water consumption by the narrowly defined categories of users (or sectors).

Estimates of the fraction reduction in water use achieved by particular measures can be obtained from the literature. The most comprehensive survey of literature on effectiveness of conservation measures has been done by the New England River Basins Commission (1980b). Table 6 contains a description of the type of information collected in that report and three other references. Unfortunately, many estimates of the "fraction reduction" in water use reported in these sources are expressed in terms of reduction in total municipal or urban water consumption or represent the aggregate effect of two or more conservation measures. Also, some of the reported fractional reductions represent engineering calculations while others are the result of actual application. The latter should be considered more reliable, although the implementation conditions of each measure must be closely examined before accepting the reduction for use in other planning situations.

Actual calculations of effectiveness of various water conservation measures is presented by Morris and Jones (1980). The authors estimated long-term water savings from metering, implementation of water-saving toilets, shower flow restrictors and reduced lot size for Denver, Colorado. Similar calculations are demonstrated in Minton et al. (1979) and Sharpe (1976). U.S. EPA (1981) provided a series of tables with the assumptions and exemplary calculations of water and energy savings for six different types of water-saving devices.

Since water conservation measures may affect different classes of water use in different ways, a disaggregate short-term water-use forecast is necessary in order to perform the effectiveness calculations. The most important task is to disaggregate actual water use into specific user sectors if such data are not available. The specific sectors for disaggregation will change from municipality to municipality. They may include (1) residential (seasonal and nonseasonal) broken down by type of housing, (2) commercial and institutional with specification of some uses such as car washing and irrigation of golf courses, (3) industrial with separation of water use by the largest customers, (4) whole sale customers, and (5) public/unaccounted-for category. The required level of disaggregation is determined by the characteristics of the specific water conservation measures being evaluated. However, if a large array of water conservation measures is to be evaluated, then the highest achievable level of disaggregation should be sought.

Table 3 in Chapter II lists a number of models that can be useful in predicting short-term unrestricted water use during drought, although the level of disaggregation is limited only to total residential and sprinkling uses. At present, the only practicable procedure for determining disaggregate water uses and projecting these uses into the future is the IWR MAIN System originally developed by the Hittman Associates, Inc. (1969). It is especially useful for application to municipalities that do not have disaggregate water use statistics, since it calculates the values of water use for over 200 categories based on economic, weather and demographic data which are easily available from the Bureau of the Census and other reports. Practical applications and discussion of this model can

TABLE 6

ESTIMATES OF EFFECTIVENESS OF WATER CONSERVATION MEASURES

CONSERVATION MEASURE(S), SOURCE	INFORMATION REPORTED	COMMENTS	REFERENCE TABLE
126			
Education, shower restrictions, low flush toilet, metering and pricing. freeze protection-leak repair	Estimates of costs and reductions in water consumption in 1978, 1980 1990, 2000, at three levels of conservation intensity for Anchorage, Alaska	Measure effectiveness based on other literature sources	Table 4, p. 494
142			
Pricing structures	Information on implementation program: location, duration, conditions, costs, water saved, money saved, and comments	Summarized 13 sources on residential, industrial/ commercial water use	Table 11, pp. 105-8
Regulation: restrictions on lawn sprinkling, car washing pool filling and average use	(as in Table 11)	Summarized 6 sources on residential, industrial/commercial, and 9 sources on public water systems	Table 13, pp. 115-7
Various education techniques	(as in Table 11)	Summarized 6 sources on residential use	Table 15, pp. 124-5
Metering	(as in Table 11)	Summarized 6 sources on residential, industrial/ commercial use	Table 17, p. 131

TABLE 6 (Continued)

ESTIMATES OF EFFECTIVENESS OF WATER CONSERVATION MEASURES

CONSERVATION MEASURE(S), SOURCE	INFORMATION REPORTED	COMMENTS	REFERENCE TABLE
142			
Leak detection and repair	(as Table 11)--Information on implementation program, location, duration conditions, costs, water saved, money saved, and comments	Summarized 9 sources on public water systems and 1 on industrial/commercial	Table 19, pp. 136-7
Pressure reduction	(as in Table 11)	Summarized 4 sources	Table 21, p. 140
62 water-saving fixtures	Cost of implementation, percent reduction in water use, comments on implementation conditions	Primary source: Milne, 1976	Table 22, pp. 145-50
Water-saving fixtures	Identifies literature sources containing information on devices listed in Table 22, indicates sources containing data on the actual use of a fixture	97 sources identified	Table 23, pp. 152-6
Water-saving fixtures, other conservation measures	Information on implementation program: location, duration, conditions, costs, water saved, money saved, and comments	Identified 30 references on residential water conservation and 20 references on industrial/commercial	Table 24, pp. 157-65

TABLE 6 (Continued)

ESTIMATES O. EFFECTIVENESS OF WATER CONSERVATION MEASURES

CONSERVATION MEASURE(S),SOURCE	INFORMATION REPORTED	COMMENTS	REFERENCE TABLE
142 Water reuse and recycle systems	(as in Table 24)	Identified 6 references on residential reuse, 22 references on industrial/ commercial, 3 references on public water systems	Table 26, pp. 175-80
Public education water conservation kits, use restrictions, others included in water conservation programs	Data on communities which have implemented water conservation	Identified 31 cases (by community or water districts)	Table 27, pp. 185-90
Water-saving devices: toilets, showers, kitchen and lavatory faucets, pressure reducing valve, hot water pipes, clothes washer, and dishwasher. Education.	Conservative estimates of costs and water/energy savings from indoor residential information		Table 7, p. 33 Table C-1, p. 86
16 Large array of water conservation measures implemented during the 1976-1977 drought	Data on communities and types of programs	57 district and communities	Tables 3.5, p. 57-60

be found in Boland (1971, 1978, 1979), and Boland et al. (1982). Thompson et al. (1976) developed a method for estimating commercial/institutional parameters for the earlier Hittman MAIN II system, which has been included in the IWR MAIN System revisions.

Finally, the third estimate needed is the coverage factor for each use sector affected by any specific conservation measure. The coverage factor, defined on the interval [0, 1], indicates the fraction of all sectoral water consumption which is used in, for example, flushing toilets. If 45 percent of total household water use in a single family residence is attributed to toilet flushing, assuming that installation of shallow trap toilets will affect 100 percent of the single-family customers, the coverage factor as applied to average day water use is 0.45.

The calculation of coverage factors can be performed using the data from those literature sources that report on fractional reduction in water use (Table 6), and from studies reporting on consumer adoption of various water conservation measures listed in Table 5.

Completion of these steps provides almost all the information that is necessary in the formulation and evaluation of alternative water conservation programs discussed in the next section.

Formulation of Water Conservation Programs

In practice, usually more than one water conservation measure will be implemented at the same time in order to achieve the desired reduction in water use. One or more measures intended for simultaneous implementation are referred to as water conservation programs. The need to formulate alternative water conservation programs is dictated by the optimization procedure used in the algorithm. The inclusion of individual water conservation measures in the optimization procedure, although theoretically possible, would considerably complicate the objective function and increase the number of constraints. At this stage of the development of the algorithm, simultaneous evaluation of a limited number of conservation programs is the most practicable solution.

When measures are combined into sets in advance, it is possible to identify possible interactions among the measures comprising a program. This allows the planner to make necessary adjustments to the total effectiveness of the program. The number of alternative conservation programs to be formulated will depend on the judgment of a planner. The only requirement is that these programs must accommodate reductions in water savings that would cover the range of actual water use. In other words, each subsequent program has to produce higher water savings than the preceding one. The resultant reductions should vary from 10 to, say, 80 percent of "normal" water consumption.

The methods of estimating total costs associated with each conservation program are presented in the next section.

Determination of Total Costs of Conservation Program

The total cost associated with the implementation of any conservation program is comprised of two elements:

(1) cost of implementation of the conservation program borne by water utility; and,

(2) monetary losses resulting from the forced reduction in water use achieved by that program which are borne by various sectors of customers.

The latter cost arises when an affected customer cannot fully realize his economic benefits due to the curtailment in water use. For instance, a sprinkling restriction imposed on residential customers will result in losses due to damages to lawns, shrubs, and flower and vegetable gardens. This loss can be approximated by lost consumer surplus which is determined from demand schedules of individual customers. Other examples of the losses that belong to the second category are those resulting from cutbacks in production by local manufacturers.

The total cost of some conservation programs may include only the implementation costs of water conservation measures. For example, a program comprised of educational campaign, free distribution of a water conservation kit, and leak detection and repair, may produce significant reduction in "normal" water use without imposing any monetary losses to customers.

The important decision in the evaluation of alternative water conservation plans relates to the definition of the object of monetary losses. Two alternative accounting formats may be used. One format may represent the losses suffered by local economy, which are measured by monetary flows to outside interests. The other format may be constructed so as to consider only those losses which are borne by water utility regardless of the regional impacts.

Two comprehensive studies of the economic losses resulting from water shortage were carried out by Russell, et al. (1970), and the U.S. Army Engineer Institute for Water Resources (Young, et al. 1972). The approach proposed in the IWR study has been adapted here to accommodate the needs of the optimization procedure. The adaptation involved selecting those accounting categories which are directly related to the evaluation of total costs of alternative water conservation programs. The accounting formats are represented by (1) water company service area which loses monetary flows to outside interests, and (2) losses suffered by water company regardless of regional impacts.

The overall purpose of the analysis is to develop separate shortage-loss relationships for those user categories which may be affected by water conservation programs. Given sectoral loss curves, the monetary losses associated with any water conservation program can be determined based on the effectiveness of that program in each sector. The level of disaggregation of water users should accommodate the evaluation of each alternative water conservation program formulated in the previous section

against the two accounting systems. However, for most practical purposes, the following shortage-loss functions should be identified for the following categories:

(1) household indoor demand
(2) residential sprinkling demand
(3) industrial demand by locally owned firms
(4) industrial demand by externally owned firms
(5) commercial/industrial demand
(6) costs borne by water utility.

Increasing cutbacks in water delivery to these users will be associated with increasing monetary losses to the area. The following sections describe the rationale and techniques for determining the shortage-loss functions in each of the above sectors.

Household Indoor Demand

Forced reduction in household water use will result in lost consumer surplus which can be clearly classified as a loss to the study area. Revenue loss associated with the reduced water use by households represents an intersector flow and should not be counted as net monetary loss to the area. Even when water utility will attempt to compensate lost revenue by introducing a surcharge on water use, the overall balance of losses remains unchanged. Nevertheless, the evaluation of the lost revenue must be carried on to produce information for the water supply manager who may choose to minimize only those losses which are sustained by water utility (alternative format).

In order to evaluate the magnitude of the lost consumer surplus and revenue, the domestic price-demand function must be known. Since, for most service areas such a relationship is not available, it must be estimated using econometric water demand models found in the literature. The domestic demand models that can be used for this purpose are those proposed by Howe and Linaweaver (1967), Danielson (1979), (see Table 3, No. 11, 3). Other models that use total residential demand may be also used, however, due to significant differences in price elasticity between domestic (in-house) and sprinkling demand, the models which disaggregate the total household usage should be preferred. The econometric models can be adopted to the study area under consideration by substituting the actual values of explanatory variables into general equation and reducing the latter to the form:

$$P = f(Q) \quad \text{or} \quad P = aQ^{b} \tag{13}$$

where Q = quantity of water demanded,

P = marginal price,

a = coefficient; and

b = reciprocal of price elasticity coefficient.

Once this relationship is determined for the study area, the estimates of the lost consumer surplus and revenue at various levels of demand reduction can be easily found.

Residential Sprinkling Demand

Forced reduction in sprinkling water use will result in the same categories of losses to the study area as those for household indoor demand. The procedure for estimating these losses is the same, however, in place of domestic demand models, the models that use sprinkling water consumption should be used. Howe and Linaweaver (1957) and Danielson (1979) also developed the relationships for sprinkling water use.

Industrial Demand by Locally Owned Firms

When a water company is forced by the shortage situation to restrict use to industrial customers which are locally owned, then the profits, after taxes, and fixed costs lost due to cut backs in production or temporary shut down, represent net monetary loss to the area. The fixed cost is included since in most cases it may be assumed that rent or mortgage payments and other capital costs associated with plant facilities will flow to outside interests. Again, the alternative accounting format will include revenue lost by water company.

The procedure proposed in the IWR report estimates the two types of losses by calculating profits plus fixed costs per production worker in each locally owned large water using company. The information sources and data needed to obtain these estimates are summarized in Table 7.

Industrial Demand by Externally Owned Firms

The losses associated with cut backs in water delivery to externally owned industrial firms include (1) loss of production payroll sustained by local employee, and (2) loss of water company revenue. Both components constitute monetary losses to the study area. These two loss functions can be estimated for each large water using company based on the information which is summarized in Table 7.

Commercial/Institutional and Public Demands

Cut backs in water delivery to the commercial/institutional sector may result in losses of receipts by commercial car washing establishments and stock losses by nurseries. These losses would be counted as losses to the area only if they could be considered as monetary flows to external interests. Since it is difficult to account for such losses, they may be assumed negligible.

Curtailed public demands which include water used by such public facilities as fire departments, parks, playgrounds, swimming pools, etc., may result in lost consumer surplus. However, since econometric demand models for such uses are not available, the estimation of losses is not possible. Moreover, the losses that might result from the lack of fire protection would be very high, and in all instances the water reserves for this purpose will not be reduced.

TABLE 7

INFORMATION AND DATA SOURCES FOR ESTIMATING INDUSTRIAL LOSSES

1. 19xx Industrial Directory (by state)

   Company's name
   Main product line
   SIC classification
   Average number of total employees

2. 19xx Census of Manufacturers (by state)

   Percent of production employees to all employees
   Average annual wages per production worker by SIC class
   Average percentage of production payroll to value of shipments by SIC class
   Value added by manufacture (less production payroll) to value of shipments by SIC class
   Industrial water consumption by SIC class

3. Quarterly Financial Report for Manufacturing Corporations (Federal Trade Commission and Securities and Exchange Commission)

   Profits after taxes per dollar of sales by SIC class

4. Interview of company personnel

   Anticipated production cut-backs in response to the 10, 20, 30, 40, 50, and 100% reduction in water supply

5. (Local) Manufacturers Association

   Ownership of industrial firms (local, external)

Costs Borne by Water Utility

The total costs borne by water company during drought emergency may include:

(1) implementation costs of water conservation measures;

(2) cost of emergency water supplies; and

(3) lost revenue due to reduced sales of water.

As mentioned earlier, in evaluation of water conservation programs, only items (1) and (3) are applicable. Regional losses are represented only by the monetary losses included in these categories which flow to outside interests. Cost of emergency water supplies has been already included at the evaluation of supply augmentation alternatives. Again, only monetary flows to outside interest are to be included if the accounting stance is representing the company's service area. While minimizing the expenses and losses that affect water utility, all three cost elements must be included regardless of whether they represent monetary flows to external or internal interests.

These steps complete the evaluation of water conservation measures arranged into alternative water conservation programs. The final product of the analysis is presented in Table 8 and 9. All numbers in these tables are hypothetical.

TABLE 8

HYPOTHETICAL LIST OF POTENTIAL WATER CONSERVATION MEASURES

Conservation Measures		Total Effectiveness[1]		Total Cost[2] $1000	
No.	Definition	%	mgd	Lump expense	Monthly cost
M1 -	Educational campaign encouraging all customers to conserve water	8	1.6	12	5
M2 -	Voluntary curtailment of lawn watering by residential customers	5	1.0	-	5
M3 -	Pressure reduction by 10 psi in entire distribution system	3	0.6	negligible	
M4 -	Water conservation kits made freely available to domestic users at central locations	5	1.0	60	
M5 -	Leak detection and repair program	15	3.0	15	8
M6 -	Water conservation kits distributed and installed by utility crews upon customer's permission	15	3.0	60	8
M7 -	Introducing emergency water with surcharge (50%) to penalize excessive users	25	5.0	-	50
M8 -	Enforced restrictions on car washing, pool filling, golf courses and landscape irrigation	15	3.0	-	20
M9 -	Rationing by fixed allocation of 40 gpcd in all households with penalties for non-compliance	40	8.0		80
M10 -	Ban on all non-essential uses with strict enforcement	60	12.0		200

(1) Effectiveness of conservation measure summed for all sectors that are affected by the measure.

(2) Including implementation costs and economic losses to consumers.

TABLE 9

ALTERNATIVE WATER CONSERVATION PROGRAMS
(HYPOTHETICAL)

Program No.	Conservation Measures Comprising the Program	Total Effectiveness after Adjustments, E_i		Total Adjusted Cost[1], L_i $1000	
		%	mgd	Lump expense	Monthly cost
1	M1	8.0	1.6	12	5
2	M2	8.5	1.0	-	5
3	M3	3.0	0.6	-	-
4	M4	5.0	1.0	60	-
5	M5	15.0	3.0	15	8
6	M6	15.0	3.0	60	8
7	M7	25.0	5.0	-	50
8	M8	15.0	3.0	-	20
9	M9	40.0	8.0	-	80
10	M10	60.0	12.0	-	200
11	M1,M2	11.0	2.2	12	8
12	M1,M2,M3	13.0	2.6	12	8
13	M1,M2,M3,M4	18.0	3.6	72	8
14	M1,M3,M5,M6	30.0	6.0	87	13
15	M1,M3,M7,M8	40.0	8.0	12	75
16	M1,M3,M5,M6,M8,M9	60.0	12.0	87	165
17	M1,M3,M5,M10	75.0	15.0	27	200

[1]One time expense (for example, for purchasing water conservation kits) + monthly cost if the measure is in effect.

CHAPTER IV

EVALUATION OF EMERGENCY WATER SUPPLIES

The drought management planning algorithm requires that the alternatives for augmenting available supply be considered along with water conservation measures. The term "emergency water supplies" is applied here to auxiliary sources that can provide limited quantity or lower quality water during periods of water shortage. Table 10 lists the most common types of such sources.

To perform the selection of optimum drought management alternatives, it is necessary to formulate each emergency water supply in terms of:

(1) availability and quality of water in potential emergency sources during persisting dry weather conditions;

(2) adequacy of existing treatment facilities to produce finished water of acceptable quality when emergency supplies make up some fraction of new water supply;

(3) lead time required to construct necessary water transmission and pre-treatment facilities (if required);

(4) construction and operation-maintenance costs required to bring emergency sources on line; and

(5) potential obstacles to implementation such as institutional barriers, right-of-way considerations, and operational permits.

This information must be available in order to increase the viability of emergency supplies when a severe drought actually happens. The sections which follow describe various activities involved in the identification and formulation of alternative emergency water supplies.

Initial Identification of Potential Supply Sources

The development of emergency water supply alternatives must begin with the identification of potential water supply sources of all types as those presented in Table 10. Although it is unlikely that a planner will overlook any sources that may be best suited for emergency utilization, it is useful to prepare an initial list of all possible sources. Each source on that list should be defined as to its (1) type (surface water, groundwater, purchased water), (2) location (distance), (3) drainage area, (4) expected water availability (high, low), (5) water quality (good, poor, unknown), (6) possible modes of transportation (pipeline, river bed), (7) existence of legal and/or institutional obstacles, (8) expected costs of transmission, and (9) other characteristics.

This initial list should represent a universe of all possible supply alternatives of which only a few will qualify for further, more detailed analysis. While listing all possible alternatives, the planner or water

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TABLE 10

ILLUSTRATIVE LIST OF EMERGENCY SUPPLIES

1. INTERDISTRICT TRANSFERS

   Interconnections:
   emergency, neighboring community, new connection

   Importation:
   by trucks, by railroad cars

2. CROSS-PURPOSE DIVERSIONS

   Alternative uses:
   hydropower, flood control, recreation

   Steam flow:
   minimum flow requirements, recharge, downstream users

3. AUXILIARY SOURCES

   Surface water:
   untapped, creeks, ponds and quarries; dead reservoir storage, temporary pipeline to a river

   Groundwater:
   abandoned wells, new wells

4. CLOUD SEEDING

manager may find out that it would be very easy to construct an interagency connection with a neighboring system which has considerable unused capacity in its supply source. Detailed topographic maps of the local area published by the U.S. Geological Survey may be very helpful in identifying various untapped sources.

Only when the initial list of alternative supplies is completed, the sources to be evaluated should be selected. Because engineering evaluation of potential sources is very costly, significant savings can be realized by reducing the number of sources to be assessed to the minimum. However, only sources that are clearly infeasible, based on various grounds, should be excluded. Where information on some source is very limited, such a source should be retained for additional data gathering.

Evaluation of Water Availability

The method of assessing available water supply in potential emergency sources will depend on the hydrologic characteristics of the source in question. Streamflow and the levels of shallow ground water aquifers are most vulnerable to drought impacts. Deep aquifers, in general, will not show abrupt drops in groundwater levels as a result of precipitation deficits.

The characteristics of streamflow that are most significant for planning drought emergency supplies include the amount and timing of extremely low discharge during drought. In order to estimate the amount of flow available in a stream with little or no storage, minimum flows of 1-, 7-, 15- and 30-day duration and occurrence intervals are of primary interest. The differentiation in timing of extremely low flows among various streams, as a result of regional drought, is also significant. It is possible that some streams may retain higher levels of flow due to different land use patterns and geological formations of their watersheds. Such differentiation would affect the amount and temporal pattern of groundwater recharge. Some shifts in timing may allow complementary utilization of several sources. There is a considerable number of studies documenting the existence of the relationship between average or extreme historical values of discharge and basin characteristics (Hill, 1978; Kuska, 1980; and Stedfast, 1979).

There are two ways of arriving at the estimate of available supply in an emergency source during drought. The first method defines the expected low flow in terms of "order statistics" of historical record, while the second, more sophisticated approach, takes into account actual soil moisture conditions at the time of forecast. The results of the former approach define probability of having specified extremely low flow in any given year, while the latter method conditions the prediction upon an actual hydrologic situation.

In the "rank-order" methods the lowest flows for the periods of various lengths in each year of record are plotted on Gumbel probability paper so that extremely low discharges can be extrapolated. One of the typical low flow estimates is 7-day 10-year discharge which gives the magnitude of the minimum 7-day streamflow having a 10 percent probability of occurrence in any given year (10-year reoccurrence interval). For

preliminary evaluation of emergency sources, the zero value of 7-day 10-year discharge may represent a cut-off line for selecting streams that are suitable for emergency supply. The selection of the streamflow of this particular duration and probability is dictated by the accessibility of this estimate from the U.S. Geological Survey publications. For streams located in Illinois and Iowa, such estimates can be found in Singh and Stall (1973), and Lara (1979), respectively. If the low flow characteristics are not available for a given stream-site, then regional regression equations relating minimum flows to basin characteristics have to be used. Hidaka (1973) provided such relationships for streams in western Washington. Comer and Zimmerman (1969) determined such relationships for small drainage basins in Vermont. Additional information can be found in Orsborn (1979).

The methods of predicting drought flows that incorporate actual soil moisture conditions and/or other measures of antecedent precipitation and temperature conditions are described in Chapter II and summarized in Table 3.

Evaluation of Water Quality

The knowledge of average or extreme values of water quality parameters in an emergency source during a period of drought is needed in order to evaluate both its suitability and treatment required before use. Quality characteristics that are of primary interest may include indicator bacteria, suspended sediment, and selected inorganic and organic constituents, including trace metals and pesticides.

One of the most critical factors likely to affect stream water quality during drought is a lack of sufficient water to dilute contaminants. This lack of dilution water suggests that quality parameters most susceptible to changes during prolonged low flows include constituents commonly found in treated effluents, i.e. dissolved solids, oxygen demanding substances, ammonia, and others. The expected changes in stream water quality during drought are discussed in Anderson and Faust (1972), Slack (1977), and Muchmore and Dziegielewski (1983).

The development of predictive multiple regression equations for assessing the effects of drought on stream water quality during drought was undertaken as the empirical research project accompanying this study. The analysis utilized water quality and streamflow data for 35 Illinois rivers at 42 locations. The predictors were comprised of 18 basin characteristics and two types of estimates of 6-year average concentrations for individual quality indicators. Water samples, used in the analysis, were collected monthly during the period of 1971-1977 which ended with the 1976-1977 drought. Two types of multiple regression equations were developed for both average and extreme concentrations of 11 water quality characteristics during the period of extremely low flow at the outset of the drought. Six measures of drought intensity (precipitation and streamflow deficits) were examined in order to make the results of the study applicable to future droughts which may vary in intensity and duration.

The sample characteristics for dependent and independent variables are summarized in Tables 11 and 12, respectively. Regression equations with

TABLE 11

WATER QUALITY CHARACTERISTICS

(C_{av} = long-term average concentration of the quality indicator.)
(C_{ab} = long-term average concentration of the parameter at base flow.)
(C_{ad} = average concentration of the parameter at the outset of drought.)
(C_{ed} = extreme concentration of the parameter at the outset of the drought.)

No.	Quality Characteristics, units	Estimated Conc.	Min	Max	Mean	SD	Number of Stations
1	T_w--Water temperature, deg. F	C_{av}	11.1	16.2	13.4	1.1	41
		C_{ab}	10.9	21.3	15.4	2.5	41
		C_{ad}	1.0	21.8	10.5	4.5	40
		C_{ed}	0.1	14.0	1.3	2.6	40
2	O_2--Dissolved oxygen concentration, mg/L O_2	C_{av}	4.7	13.4	9.1	1.6	40
		C_{ab}	3.5	17.4	8.7	2.7	41
		C_{ad}	1.9	16.8	9.2	3.1	40
		C_{ed}	0.1	38.4	10.7	7.3	36
3	O_2D--Dissolved oxygen deficit, percent	C_{av}	0.0	55.1	14.7	13.6	41
		C_{ab}	0.0	65.9	18.4	19.7	41
		C_{ad}	0.0	83.4	21.1	23.7	41
		C_{ed}	0.0	100.0	33.4	29.3	36
4	pH--Hydrogen ion concentration	C_{av}	6.9	8.6	7.9	0.3	41
		C_{ab}	6.1	8.5	7.9	0.4	41
		C_{ad}	6.9	8.6	7.9	0.4	41
		C_{ed}	6.8	8.5	7.8	0.4	41

C_{ad}, C_{ed} dependent variables

C_{av}, C_{ab} independent variables

TABLE 11 (Continued)

WATER QUALITY CHARACTERISTICS

(C_{av} = long-term average concentration of the quality indicator.)
(C^{ab} = long-term average concentration of the parameter at base flow.)
(C^{ad} = average concentration of the parameter at the outset of drought.)
(C_{ed} = extreme concentration of the parameter at the outset of the drought.)

No.	Quality Characteristics, units	Estimated Conc.	Min	Max	Mean	SD	Number of Stations
5	P--Total phosphorus concentration, mg/L P	C_{av}	0.04	4.85	0.80	1.15	41
		C^{ab}	0.03	6.40	1.12	1.75	41
		C^{ad}	0.02	6.20	1.11	1.62	41
		C_{ed}	0.01	6.80	1.29	1.97	40
6	COLI--No. of fecal coliforms, logarithmic average, No./100 ml	C_{av}	4000	6,770	765	1,262	41
		C^{ab}	14	6,191	625	1,190	41
		C^{ad}	5	149,666	6,462	26,429	40
		C_{ed}	1	50,000	2,814	9,393	34
7	NH_3--Ammonia nitrogen concentration, mg/L NH_3-N	C_{av}	0.12	8.46	1.31	2.25	41
		C^{ab}	0.07	13.35	2.05	3.63	40
		C^{ad}	0.03	14.57	2.16	3.71	40
		C_{ed}	0.01	14.00	3.48	4.67	39
8	NO_2+NO_3--Nitrate and nitrate nitrogen concentration mg/L (NO_2+NO_3)-N	C_{av}	0.34	8.52	2.41	1.69	40
		C^{ab}	0.15	4.97	1.43	1.25	40
		C^{ad}	0.03	15.00	1.79	2.88	41
		C_{ed}	0.01	13.10	1.87	3.15	39

C^{ad}, C_{ed} dependent variables

C_{av}, C^{ab} independent variables

TABLE 11 (Continued)

WATER QUALITY CHARACTERISTICS

(C = long-term average concentration of the quality indicator.)
(C_{av} = long-term average concentration of the parameter at base flow.)
(C_{ab} = average concentration of the parameter at the outset of drought.)
(C_{ad} = extreme concentration of the parameter at the outset of the drought.)
(C_{ed}

No.	Quality Characteristics, units	Estimated Conc.	Min	Max	Mean	SD	Number of Stations
9	SPCON--Specific conductance, mohms	C	166	1,757	781	348	41
		C_{av}	174	2,563	973	587	41
		C_{ab}	174	2,617	908	519	35
		C_{ad}	200	2,780	1,026	500	35
		C_{ed}					
10	Fe--Total iron, mg/L Fe	C	0.36	5.64	1.82	1.21	40
		C_{av}	0.19	2.96	1.01	0.69	41
		C_{ab}	0.10	4.90	0.97	0.85	37
		C_{ad}	0.01	1.70	0.66	0.45	27
		C_{ed}					
11	Mn--Manganese, mg/L Mn	C	0.07	3.69	0.46	0.64	41
		C_{av}	0.06	4.85	0.56	0.86	41
		C_{ab}	0.04	2.52	0.52	0.57	38
		C_{ad}	0.03	5.00	0.70	1.14	24
		C_{ed}					
12	Cl--Chloride, mg/L Cl	C	3	309	69	73	41
		C_{av}	3	379	85	98	41
		C_{ab}	4	354	86	95	39
		C_{ad}	4	450	97	119	28
		C_{ed}					

C_{ad}, C_{ed} dependent variables

C_{av}, C_{ab} independent variables

TABLE 11 (Continued)

WATER QUALITY CHARACTERISTICS

(C_{av} = long-term average concentration of the quality indicator.)
(C_{ab} = long-term average concentration of the parameter at base flow.)
(C_{ad} = average concentration of the parameter at the outset of drought.)
(C_{ed} = extreme concentration of the parameter at the outset of the drought.)

No.	Quality Characteristics, units	Estimated Conc.	Min	Max	Mean	SD	Number of Stations
13	SO_4--Sulfate, mg/L SO_4	C_{av}	23	852	130	159	41
		C_{ab}	22	1,256	163	244	41
		C_{ad}	19	1,247	157	241	39
		C_{ed}	22	1,640	197	347	28
14	TURB--Turbidity, JTU	C_{av}	6	265	50	48	40
		C_{ab}	6	57	23	14	32
		C_{ad}	4	18	9	4	12
		C_{ed}	1	27	7	7	12
15	HARD--Hardness, mg/L $CaCO_3$	C_{av}	166	858	321	128	37
		C_{ab}	210	1,052	410	231	22
		C_{ad}	223	1,077	410	228	12
		C_{ed}	229	1,220	437	279	11
16	ALK--Alkalinity, mg/L$CaCO_3$	C_{av}	48	300	197	59	38
		C_{ab}	59	352	225	67	25
		C_{ad}	145	371	232	63	14
		C_{ed}	140	398	251	77	13

C_{ad}, C_{ed} dependent variables

C_{av}, C_{ab} independent variables

TABLE 12

LIST OF INDEPENDENT VARIABLES

No.	Description and Unit	Variable Code	Min	Max	Mean	SD	Number of Stationary
		HYDROLOGIC VARIABLES					
1	Drainage area, sq. mi.	A	11.5	9551	1334	2162	42
2	Channel length, mi.	H	9.8	237.9	71.5	04.9	34
3	Average discharge, cfs	Q_{av}	11.6	10,680	1082	1984	41
4	Average annual runoff, in/yr	R	7.82	18.77	10.38	2.23	38
5	7-Day 10-year flow as percent of average discharge	B	0	30.34	5.54	7.84	41
6	Municipal effluent discharge as percent of average discharge	E_m	0	21.49	3.37	6.25	39
8	Industrial effluent discharge as percent of average discharge	E_i	0	5.99	0.23	0.96	39
		CLIMATOLOGICAL VARIABLES					
9	Average annual precipitation,in.	F	31.98	45.05	37.05	3.42	39
10	Average annual temperature, in.	T	46.3	57.6	52.1	2.89	39
11	Twelve-month precipitation deficit, (March 1976-February 1977), percent below normal	D_{12}	10.21	37.34	24.13	7.13	39

TABLE 12 (Continued)

LIST OF INDEPENDENT VARIABLES

No.	Description and Unit	Variable Code	Min	Max	Mean	SD	Number of Stationary
12	Six-month antecedent precipitation deficit for drought quality sampling, percent below normal	D_6	11.44	58.30	38.63	11.09	39
13	Three-month antecedent precipitation deficit for drought quality sampling, percent below normal	D_3	24.11	78.09	54.66	14.98	39
14	One-month antecedent precipitation deficit for drought quality sampling, percent below normal	D_1	8.29	97.13	63.20	19.53	39
	LAND USE VARIABLES						
15	Fraction of drainage area in harvested cropland, percent	L_1	6.93	88.06	53.96	24.28	39
16	Fraction of drainage area in idle cropland, percent	L_2	0.43	1.83	1.24	0.32	39
17	Fraction of drainage area in woodland, percent	L_3	0.20	13.96	4.38	3.04	39
18	Fraction of drainage area in house lots, ponds, roads, wastelands, percent	L_4	0.47	9.04	3.53	1.43	39

TABLE 12 (Continued)

LIST OF INDEPENDENT VARIABLES

No.	Description and Unit	Variable Code	Min	Max	Mean	SD	Number of Stationary
19	Fraction of drainage area in pastureland, percent	L_5	0.27	24.23	7.56	5.87	39
20	Fraction of drainage area in cropland on which commercial fertilizer is used, percent	L_6	3.83	51.93	34.17	14.10	39
	STREAMFLOW VARIABLES						
21	Average instantaneous streamflow for sampling during drought as percent of average discharge	Q_d	0.81	37.19	11.48	12.07	42
22	Instantaneous streamflow during sampling at the outset of drought as percent of average discharge	Q_r	0.26	29.31	9.15	10.16	41

predictor coefficients significant at 0.05 probability level are presented in Table 13 and 14. The applicability of these equations for other regions of the country has not been evaluated, therefore, they should be used with caution.

Other statistical water quality models can be also used for initial assessment of the potential impacts of drought on streamflow. Many researchers approached the problem of water quality modeling by assuming the existence of a significant correlation between the concentration of a given constituent and discharge expressed in terms of a "rating curve" which can be represented as:

$$C_k = aQ^b \qquad (14)$$

where: C_k = concentration of a constituent k;

Q = instantaneous streamflow;

a,b = coefficients which depend on drainage basin characteristics.

Betson and McMaster (1975) determined regional water quality prediction equations of this form based on 66 watersheds in the Tennessee Valley. A total of 15 constituents were examined in relation to streamflow, the fraction of watershed in forest and four geologic characteristics. The authors established significant equations for the a term for all constituents except color, however, the b term equations, significant at 0.10 level, were obtained only for silica, magnesium, sodium, sulfate, and calcium carbonate. One of the most comprehensive investigations of the statistical relationships between water quality and basin characteristics was done by Lystrom, et al. (1978).

Other studies that utilized multiple regression models to relate water quality to basin characteristics include those by Branson and Owen (1970), Flaxman, (1972); Hindall (1976), Steele and Jennings (1972), Schlosser and Karr (1980), and Vendl (1979). Although the models reported in these studies did not attempt to predict streamflow quality during drought, some of them include streamflow as explanatory variable and can be useful in evaluating concentration of a constituent in question during drought flows. The problem with this practice is that the reported relationships were determined based on both high and low streamflow conditions and their application at extremely low flow may produce a significant error of estimate.

Determination of Adequacy of Existing Treatment Facilities

When emergency source supplies a fraction of raw water, the existing treatment facilities may fail to produce finished water of acceptable quality. Many characteristics of water quality can be upgraded by increasing doses of chemicals that are normally used in a treatment process such as polyelectrolytes, alum, lime, ozone, chlorine and other agents. Sometimes, powdered activated carbon may be introduced to eliminate taste and odor problems present in water from emergency supplies. In each case,

TABLE 13

REGRESSION EQUATIONS FOR AVERAGE CONCENTRATION OF WATER QUALITY INDICATORS DURING DROUGHT

Dependent Variable (4)	Eq. No.	Regression Equation with Unstandardized Coefficients	R^2	Selected Statistics S.E.(2)	S.E./X(3) *100%	F-statistic	N
O_2	1a	$-2.65 + 0.854\ C_{ab}^{(4)} + 0.781\ A^* + 0.035\ D_n$	0.86	1.12	12	67.7	38
	1b	$6.02 - 0.399\ E_m^{ab} + 0.451\ D_1 + 0.123\ Q_d^n$	0.47	2.17	24	9.90	38
O_2D	2a	$102.7 + 1.100\ C_{ab} - 2.539\ F - 0.643\ Q_d$	0.82	10.5	50	52.5	39
	2b	$20.39 + 3.077\ E_m^{ab} - 0.823\ Q_d$	0.35	19.6	93	9.61	39
pH	3a	$4.93 + 0.405\ C_{ab} - 0.010\ D_6 + 0.017\ Q_d$	0.91	0.12	1.5	126.4	39
	3b	$7.50 - 0.036\ L_3^{ab} + 0.011\ L_6 + 0.018\ Q_d$	0.57	0.26	3.3	15.2	39
F	4a	$0.091 + 0.908\ C_{ab}$	0.96	0.32	29	957.1	40
	4b	$-1.97 - 0.153\ B^{ab} + 0.405\ E_m + 0.045\ L_6 + 0.027\ D_6$	0.92	0.48	44	95.6	38
COLI*	5a	$-1.33 + 0.970\ C_{ab}^* + 0.696\ D_1^*$	0.78	0.35	16	58.0	36
	5b	No significant relationship established	--	--	--	--	--
NH_3	6a	$0.541 + 0.355\ C_{ab} + 0.428\ E_m + 0.705\ E_i - 0.062\ Q_d$	0.85	1.52	71	46.8	39
	6b	$0.733 + 0.614\ E_m^{ab} + 0.897\ E_i - 0.073\ Q_d^i$	0.81	1.68	78	47.3	38
NO_2+NO_3	7a	$-0.591 + 1.857\ C_{ab} - 0.036\ L_1 + 0.069\ D_{12}$	0.85	1.15	65	65.6	39
	7b	No significant relationship established	--	--	--	--	--
SPCOL	8a	$256.6 + 0.446\ C_{ab} - 29.1\ L_3 + 4.10\ D_3$	0.98	54	6.6	452.7	33
	8b	No significant relationship established	--	--	--	--	--

TABLE 13 (Continued)

REGRESSION EQUATIONS FOR AVERAGE CONCENTRATION OF WATER QUALITY INDICATORS DURING DROUGHT

Dependent Variable (4)	Eq. No.	Regression Equation with Unstandardized Coefficients	R^2	Selected Statistics S.E.(2)	S.E./$\bar{X}$(3) *100%	F-statistic	N
Fe	9a	$3.41 + 0.121\ C_{ab} - 0.161\ R - 0.018\ D_3$	0.84	0.35	36	53.9	33
	9b	$1.94 + 0.085\ L_3^{ab} - 0.025\ D_3$	0.34	0.71	73	8.52	36
Mn	10a	$0.880 + 0.078\ C_{ab} + 0.023\ L_5 - 0.013\ D_6 - 0.012\ Q_d$	0.89	0.20	38	65.2	37
	10b	$1.43 + 0.034\ L_5^{ab} - 0.031\ D_6$	0.59	0.37	71	24.9	37
Cl	11a	$25.0 + 0.601\ C_{ab} + 6.847\ E_m - 1.215\ Q_d$	0.89	33	39	91.7	38
	11b	$55.0 + 16.18\ E_m^{ab} - 2.170\ Q_d$	0.79	45	54	64.9	38
SO_4	12a	$22.0 + 0.817\ C_{ab} - 0.922\ Q_d$	0.86	27	27	99.5	36
	12b	$87.0 + 8.735\ E_m^{ab} + 25.59\ E_1 - 2.00\ Q_d$	0.43	55	56	7.46	34

*Variable in logarithmic form (base 10)
(1) Standard error of estimate.
(2) Standard error of estimate as percent of mean value of dependent variable.
(3) All variables are defined in Tables IV-2 and IV-3.
(4) C_{ab} designates long-term average concentration of the quality indicator at baseflow.

TABLE 14

REGRESSION EQUATIONS FOR EXTREME CONCENTRATION OF WATER QUALITY INDICATORS DURING DROUGHT

Dependent Variable (4)	Eq. No.	Regression Equation with Unstandardized Coefficients	Selected Statistics R^2	S.E.(2)	S.E./X(3) *100%	F-statistic	N
O_2	1a	$-3.67 + 0.943\ C_{ab}$(4)$+ 0.073\ D_1$	0.45	3.37	37	11.7	32
	1b	$4.00 - 0.240\ E_m^{ab} + 0.093\ D_1$	0.24	3.97	44	9.05	32
O_2D	2a	$36.70 + 0.935\ C_{ab} - 0.348\ D_1$	0.56	18.7	58	19.5	34
	2b	$41.90 + 2.293\ L_m^{ab} + 1.667\ L_5 - 0.484\ D_1$	0.36	22.8	71	5.59	34
pH	3a	Not significant	--	--	--	--	--
	3b	Not significant	--	--	--	--	--
P	4a	$-0.390 + 0.875\ C_{av}$(5)$- 0.061\ B + 0.186\ E_m - 0.018\ D_6$	0.95	0.46	36	155.5	38
	4b	$0.290 - 0.158\ B^{av} + 0.370\ E_m + 0.067\ Q_r^m$	0.92	0.56	44	144.0	39
COLI*	5a	$-0.286 + 0.856\ C_{ab}^* + 0.024\ Q_r$	0.54	0.62	32	16.9	32
	5b	Not significant	--	--	--	--	--
NH_3	6a	$1.91 + 0.558\ C_{ab} - 0.068\ L_1 + 0.073\ D_3$	0.64	2.90	85	20.2	38
	6b	$2.28 - 0.346\ F_m^{ab} - 0.058\ L_1 + 0.066\ D_3$	0.66	2.83	83	21.6	38
NO_2+NO_3	7a	$-0.730 + 2.022\ C_{ab} - 0.045\ L_1 + 0.087\ D_{12}$	0.88	1.14	62	82.0	38
	7b	$19.09 - 0.430\ F^{ab} - 0.059\ L_1 + 0.080\ D_{12}$	0.50	2.29	125	11.5	38

TABLE 14 (Continued)

REGRESSION EQUATIONS FOR EXTREME CONCENTRATION OF WATER QUALITY INDICATORS DURING DROUGHT

Dependent Variable (4)	Eq. No.	Regression Equation with Unstandardized Coefficients	Selected Statistics R^2	S.E.(2)	S.E./X(3) *100%	F-statistic	N
SPCON	8a	$938.0 + 0.368\ C_{ab} - 67.88\ R - 20.10\ L_3 + 7.56\ D_3$	0.82	144	15	28.9	30
	8b	$1624.0 - 69.43\ R^{ab} + 45.47\ E_m - 12.63\ Q_r^3$	0.45	250	27	7.00	30
Fe	9a	$3.95 + 0.052\ C_{ab} + 0.080\ L_3 - 0.089\ F - 0.005\ D_1 - 0.015\ Q_r$	0.83	0.21	32	19.2	26
	9b	$0.582 + 0.076^{ab} L_3 + 0.179\ E_i - 0.005\ D_1$ (6)	0.49	0.34	51	6.85	25
Mn	10a	$3.23 + 0.203\ C_{ab} - 0.177\ R - 0.204\ D_6$	0.82	0.52	74	27.5	21
	10b	$6.69 - 0.185\ R^{ab} - 0.025\ L_1 - 0.072\ D_3^6$	0.56	0.82	117	7.55	22
Cl	11a	$22.0 + 0.757\ C_{ab} + 9.241\ E_m - 2.329\ Q_r$	0.97	23	24	255.9	27
	11b	$-46.0 + 19.080\ E_m^{ab} + 3.312\ D_6^m - 5.332\ Q_r^r$	0.92	36	38	86.1	27
SO_4	12a	$24.0 + 0.765\ C_{ab} - 1.220\ Q_r$	0.83	29	30	52.3	24
	12b	$149.0 + 4.155\ E_m^{ab} + 25.96\ E_i^r - 3.170\ D_{12}$	0.46	53	56	5.52	24

*Variable in logarithmic form (base 10)
(1) Variables are defined in Tables IV-2 and IV-3.
(2) Standard error of estimate
(3) Standard error of estimate as percent of mean value of dependent variable.
(4) C_{ab} designates long-term average concentration of the quality indicator at baseflow.
(5) C_{av} designates long-term average concentration of the quality indicator.

the capability of a system to handle such problems must be evaluated. If emergency source is obtained directly from a river, then in most cases some pretreatment facilities will be required in order to eliminate excessive quantities of suspended solids, which cannot be accommodated by existing sedimentation and sludge disposal units of the treatment plant. High content of algae in lakes, ponds and quarries may result in a similar problem.

Another important consideration which is related to water quality in an emergency source is protection of various units of the water supply system against possible damages. One of the most common problems is related to the protection of a reservoir against accelerated siltation or algae blooms. These problems may arise when water from a nearby river or other source is pumped to the reservoir which is a primary source of supply. Some treatment facilities are also vulnerable to damages caused by excessive quantities of pollutants in raw water. For instance, if granulated activated carbon (GAC) process is used, then high loadings of organic matter may easily exhaust its adsorption capacity. Finally, distribution systems must be protected against the deposition of algae and nutrients, scale build-up or corrosion. The latter may occur when the corrosivity index of finished water is altered by the presence of carbonates or carbon dioxide in emergency supplies.

While the above problems can be dealt with by adjusting treatment technologies or by preliminary treatment of water from emergency supplies, concentrations of some constituents may be reduced only by dilution. These constituents may include chloride, sulfate, total dissolved solids, and nitrates. Treatment facilities which are used to remove these substances (such as ion exchange resins) are not usually present in treatment plants producing water for drinking purposes.

The optimization procedure used in the algorithm contains a set of constraints that limit the quantities of supplemental water when there is a need for good quality dilution water. These constraints are mathematically formulated in Chapter 1. The information which has to be supplied includes concentration of a constituent in both primary and emergency sources of water and its maximum permissible value in finished water.

Useful references in the assessment of necessary treatment of water from emergency supplies include water technology textbooks, treatment plant operator manuals and various reports found in the American Water Works Association publications.

Determination of Construction and Operation-Maintenance Costs and Lead Time

The cost relationships required by the optimization procedure should be defined as linear functions of the quantity of water obtained from an emergency source. When cost estimates must be provided for a large number of alternatives, the identification of detailed cost categories similar to accounting practices is impractical. The most appropriate approach is to use statistically determined cost relationships that utilize a small number of explanatory variables, such as capacity, distance, elevation, and water quality.

Water supply cost functions proposed in the literature usually relate to four major cost categories: acquisition, treatment, transmission, and overhead. The cost categories applicable to the emergency supplies are related to the above in a special way. They include the cost of acquisition, which is comprised of the cost of collection of raw water from a source with cost of pumping facilities, labor, and energy as its major components. Treatment cost related to emergency supplies will be only those of chemicals and power, while any capital outlays on additional treatment facilities will not be present except those for pre-treatment installations. The third category, transmission costs, may constitute the largest portion of emergency supply cost, even if piping is only temporary and can be salvaged after the emergency situation. Therefore, the cost functions applicable to emergency supplies are those for disaggregated categories, especially treatment costs.

Cost Functions

The literature sources which attempted to provide statistical relationships for transmission and treatment cost use three types of cost estimates: total cost, capital cost, and operation and maintenance cost. Most functions relate these costs to a single explanatory variable such as system capacity or average daily flow by means of an exponential relationship. For example:

$$C = aQ^b \tag{15}$$

where, C = total (or capital, or O&M) cost;

Q = capacity in mgd;

a = coefficient representing the cost of one capacity unit. e.g. 1 mgd plant; and

b = coefficient representing the elasticity of cost with respect to capacity.

Similar functions can be adopted to determine the treatment cost categories relevant to emergency supplies such as cost of chemicals, and in some cases, energy. Where preliminary treatment processes like sedimentation, softening or disinfection are needed, then the relationships which serve to estimate costs of unit operations and unit processes may be used. Gumerman et al. (1978, and 1979) developed a number of curves for estimating construction and operation and maintenance cost curves for various unit processes of water treatment. Other sources that provide statistical relationships for estimating water treatment costs include Hinomoto (1971 and 1977), Hines (1969), Ford and Wanford (1969), Stevie et al. (1979), and Gutman and Clark (1978).

In estimating water transmission costs for emergency supply systems, two basic cost components must be considered. These are: (1) capital cost consisting of the construction cost of pumping station and pipelines, and (2) operation-maintenance costs including energy and repair costs incurred in the transmission of water. Ackerman (1967) determined the functional

relationship for estimating the capital cost of pipeline based on the pipe diameter as:

$$C_p = 2.16\ D^{1.2} \qquad (16)$$

Where: C_p = construction cost for a transmission line in the 1964 dollars per mile; and

D = pipe diameter in inches.

Linaweaver and Clark (1964) developed a similar relationship with the value of the exponent of 1.29. The cost functions for estimating the capital cost of a pumping station can be found in Singh (1971) and Aron et al. (1975). Both relationships use the installed horsepower as an explanatory variable.

The second component of transmission cost, the operation-maintenance cost, is often related to volume, maximum expected pumping head, annual hours of plant operation, or is calculated as a function of the capital cost or pipeline or pumping station (Aron, et al. 1975).

In addition to the studies mentioned above, a number of complete cost estimating procedures are available from the literature. The U.S. Army Engineers, Waterways Experimental Station (WES) developed a computer program called the Methodology of Areawide Planning Studies (MAPS) which includes recently updated cost estimating procedures (U.S. Army Engineers, 1980; Lamm and Walski, 1983). This procedure can be used to estimate costs for such facilities as dams, force mains, pump stations, open channels, storage tanks, tunnels, water treatment plants, and wellfields. Several sources that contain valuable data on cost estimation are collected in Table 15. Additional information can be found in Murphy and Associates, Inc. (1981), Dickson (1978), Pound et al. (1979), and Dowes (1970).

In order to provide necessary cost inputs into the algorithm, the functional relationships reported in the above sources must be aggregated so that they represent total cost functions for individual emergency water supply sources. Three problems may arise in the preparation of such functions. First, in many literature sources, the cost estimation procedures do not specify functional forms. They either rely on cost curves or cost tables. Therefore, it may be necessary to express these relationships in functional forms. Second, the optimization element of the algorithm assumes linear cost functions while most empirical data uses exponential equations. For this reason, it is necessary to linearize the total cost function for each source. This may be done by determining the most likely capacity (or yield) interval for each source and substituting the curve for that interval by a straight line characterized by an average total cost coefficient which must be specified in the objective function. Finally, while determining individual cost functions, it is necessary to update both the construction and O&M costs by means of appropriate cost indexes. This may cause considerable problems when cost relationships are adopted from various sources. Special care should be taken in order to maintain consistency among various indexes used in the updating process.

TABLE 15

LITERATURE REFERENCES FOR COST ESTIMATION

Source	Items	Comments
75	Cost curves for 99 water treatment unit processes applicable to treatment capacities between 2,500 gpd to 200 mgd.	Included computer program user's manual for the cost curves.
74	Intermediate report, cost curves for 30 unit processes of water treatment.	Cost curves also induced in EPA 600/2-79-162.
76	Computer programs for calculating costs for chlorination, chlorine dioxide, chloramunation, ozone, and granular activated carbon adsorption.	Cost adjustments to current dollars using EPA's Contamination Cost Index, Wholesale Price Index, and Labor Cost Index.
177	Chemical, labor, and O&M costs for small water treatment systems.	Data based on 23 utilities studied.
138	Cost for force mains, and pump stations.	Data derived from winning bid documents of projects funded by P.L. 92-500.
182	Cost estimates, for dams, pipes, pumping stations, open channels, storage tanks, tunnels, water treatment plants and wellfields.	MAPS (Methodology for Areawide Planning Studies)
8	Statistical cost functions for surface reservoir, intake structure, transmission line, pumping station, electrical power, treatment plant, chlorination system, coagulation, flocculation and rapid sand filtration, wellfield, lime-soda softening.	

Construction and Start-up Lead Time

A necessary time between conceptual plan to utilize a given emergency source and operation start-up may have a significant effect on the quantity of water that can be obtained from that source. Even if emergency sources are identified and plans for construction and operation prepared in advance, it still may take one or two months before water can be obtained from the source.

The estimate of the lead time for each alternative source must be provided by the planner. The literature sources that describe past drought experiences may provide helpful information on this subject (see Chapter I).

Legal/Institutional Obstacles

Apart from technical and economic evaluation of emergency water supplies, the investigation of potential legal/institutional obstacles must be carried out to determine whether a given emergency source is feasible on such grounds. Every state establishes basic rules for the issuance of permits for construction, modification and operation of water supply systems. Utilization of emergency supplies will require special permits from such an agency. If emergency supplies are planned for in advance, then obtaining necessary permits should not create problems. During water shortage situations, it will be necessary to apply for emergency construction or operation permits. Additional problems may be encountered while acquiring rights-of-way, or arranging cross-purpose diversions or interbasin transfers of water.

CHAPTER V

MATHEMATICAL OPTIMIZATION PROGRAMMING

The descriptive data on individual drought management measures discussed in Chapters III and IV must be integrated so that optimum plans can be identified. The professional, legal, political, and social considerations leading to the formulation of alternative drought management measures may be further aided by utilization of system analysis techniques. These techniques may be helpful in assessing the economic and engineering consequences of alternative courses of action, which may not be explicitly identified while a piecemeal approach is used. The system analysis techniques are capable of integrating the quantities and costs of water obtained by implementing various management actions and expected water supply and demand into ~~a model which~~ will minimize total cost of shortage mitigation strategies for a chosen accounting stance. The selection of appropriate techniques will depend largely on the formulation of planning objectives and constraints. The following sections review several system analysis techniques which are most widely used in water resource management.

Mathematical Programming Optimization Techniques

Linear Programming

Linear programming developed in 1947 by a research team led by George B. Dantzig (Dantzig, 1963) has been one of the most widely used in the water resources field during the early 1970s. This procedure solves for unknowns in a linear, additive objective function subject to a set of linear constraints. The unknowns are often referred to as "decision variables" or "activity levels." The application of this technique to problems of water quality and water quantity management has been reviewed by Drobny (1971). Joeres et al. (1971) and DeVries and Clyde (1971) used linear programming techniques to solve a multiple source water supply problem. Some studies used linear programming for determining the optimal investment paths in the development of an urban water supply system (Hoppel and Viessman, 1972).

Many water resource planning situations, however, are not amenable to analysis by linear programming because of nonlinear objective functions or constraints. Therefore, other techniques have become popular in the most recent optimization studies.

Nonlinear Programming Approaches

Nonlinear programming procedures solve optimization problems which are formulated as nonlinear models. Two techniques are available to solve such problems: (1) the large-scale generalized reduced gradient (LSGRG) method, and successive linear programming (SLP) algorithms. The LSGRG techniques are described by Ocanas and Mays (1980). Successive linear programming is based on sequence of linear programming applications (Palacios-Gomex at al. 1981). In this iterative process the objective

function is successively linearized and at each step a separate linear program is solved.

The nonlinear programming methods were used by Ocanas and Mays (1981) to solve water reuse planning problems, and by Mulvihill and Dracup (1974) to optimize timing and sizing of a conjunctive water supply and wastewater treatment system for Los Angeles.

Generally, the nonlinear programming techniques involve a high degree of mathematical sophistication although their application is facilitated by availability of ready-to-use computer software.

Integer and Mixed Integer Programming

The inclusion of water conservation programs into objective function imposes still another requirement on the optimization technique. Since water conservation programs are best represented by logical variables, the most suitable solution technique is mixed integer programming.

Integer programming is a simple extension of linear programming with some or all decision variables that may assume only integer values. Mixed integer programming solves, for both integer and continuous variables, in objective function. The integer variables allow the implement/do not implement option for alternative water conservation programs which reflects the actual planning situation.

Hughes, et al. (1976), and Pugner and Hughes (1978) applied integer and mixed integer programming models for solving water supply planning problems. In the latter, integer variables were used to separate investment costs from O & M costs, which were represented as continuous variables. Lindsay and Dunn (1982) used a mixed integer programming model to identify the least cost of water supply augmentation for three New Hampshire towns. Lauria (1975) demonstrated the usefulness of this technique in regional sewerage planning.

The mixed integer programming algorithms are best suited for the evaluation of a number of alternatives, of which some cannot be represented by means of continuous decision variables.

Alternative Model Formulations

The optimization model presented in Chapter I integrates both hydrologic and economic aspects of drought management planning situations. However, additional research areas needed for the improvement of the present model are obvious. These include:

(1) applications of solution techniques allowing for nonlinear forms of continuous variables in the objective function;

(2) direct inclusion of individual conservation measure variables into objective function; and

(3) incorporation of alternative accounting stances as minimization objectives.

The inclusion of nonlinear continuous decision variables into the model would eliminate the need to determine cost coefficients that change with the magnitude of these variables. These problems can be solved by use of nonlinear programming approaches. More difficult is the incorporation of individual water conservation measures because of a large number of constraints that have to be included in order to make necessary adjustments in the effectiveness of individual measures resulting from possible interactions.

Finally, the most important problem is associated with the application of alternative accounting stances, i.e., the geographical area, or a party from whose point of view the economic impacts are minimized. The alternative accounting stances translate to alternative cost coefficients for decision variables. This may be accomplished by formulating alternative cost relationships for each drought management measure in advance.

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AD-A138 430 EVALUATION OF DROUGHT MANAGEMENT MEASURES FOR MUNICIPAL AND INDUSTRIAL WATER SUPPLY(U) SOUTHERN ILLINOIS UNIV CARBONDALE DEPT OF GEOGRAPHY B DZIEGIELEWSKI ET AL. 2/2

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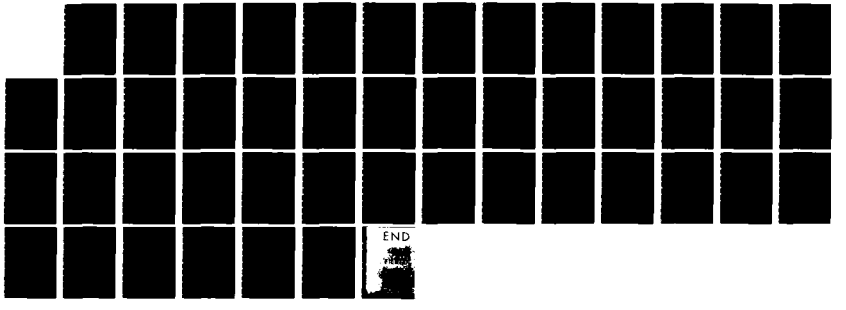

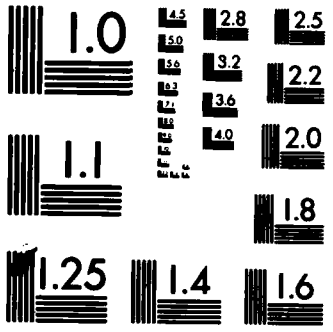

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APPENDIX

AN ANNOTATED BIBLIOGRAPHY ON DROUGHT CONTINGENCY PLANNING

This appendix contains annotations of selected references which contain useful information for the preparation of drought management plans.

1
Abbott, H. E., K. G. Cook, and R. B. Sleight. 1972. Social Aspects of Urban Water Conservation. Century Research Corporation. Report prepared for the Office of Water Resources Research.

This report presents the results of a survey of the managers and the customers of 17 Eastern United States water utilities that imposed short-term restrictions on uses of water outside and appealed for less use inside the house.

The survey of customers revealed that most agreed that outside uses are least essential (only 5 to 12% of the respondents rated stoppage of various outside uses to involve "much" inconvenience compared to 41 to 54% for various inside uses). These measures achieved from 18 to 50% reduction in water use with voluntary measures being as effective as compulsory. The authors recommend voluntary measures be tried first. Most consumer respondents (80%) did not want restrictions in normal times, but half of the respondents were not willing to pay 10% more for their water to insure adequate supplies. In drought areas, 75% of the respondents preferred metered to flat rates. There was strong objection (92% of the respondents) to dyeing or giving the water an unpleasant taste as a warning to consumers to save water. Estimates by respondents of the amount of water used for various purposes were wildly inaccurate, indicating that instruction from public officials on in-house water reduction should be very specific rather than call for percent reductions or for limits to a specific number of gallons per person per household.

The report concludes: (1) People of the Eastern United States are quite ignorant of their water use and supplies. Most people are willing to save water in emergencies but don't know how. A continuing educational campaign by the utilities to correct this situation is needed. (2) Emergency restriction plans should be prepared in advance (examples are given). Most respondents preferred that the declaration of emergency come from the water official (60%) than other city official (23%). But the report notes that the water official may be too busy to make a public announcement. One of the most important aspects of an emergency plan is to have all information funneled through one office to avoid confusion. Most often lacking were official announcements of the end of the emergency.

7
Anderson, P. W., S. D. Faust, and J. E. McCall. 1972. Impacts of Drought on New Jersey's Water Resources. Journal of the Irrigation and Drainage Division.

The authors discuss the impacts of the 1961-1966 drought on the water resources of New Jersey. The persisting precipitation deficiency of about 25 percent during that period caused deterioration of water quality, decreases in streamflow, and depletion of storage in water supply reservoirs.

The adjustments to drought included issuing a State-of-Emergency Proclamation for the populated northeastern part of the State. The array of water conservation measures included:

(1) limited air conditioning in commercial establishments;
(2) shut down swimming pools and fountains;
(3 prohibited automobile washing and lawn sprinkling;
(4) directed early completion of several water-supply construction programs; and
(5) implemented programming to further interconnect water-transmission systems.

The article also includes a discussion of many environmental impacts related to the drought.

5
Anderson, Raymond W. 1967. Pawtucket, Rhode Island and the Drought. Journal of New England Water Works Association 81(3):301-303.

This article describes the response of the City of Pawtucket to the water supply shortage during the 1964-1966 drought. Plans for alleviating the effects of drought were formulated by the mayor, the Water Conservation Committee, Chamber of Commerce and all local businesses and industries.

The emergency plan was comprised of two ordinances: (1) ban on all use of water for watering lawns, car washing and any unnecessary use when the reservoir supply dropped below 50 percent; and (2) ban on the use of water for air-conditioning without recirculation. When both of these ordinances were put in force, they resulted in savings of about 25 gallons per capita per day, or 16 to 18 percent of expected unrestricted demand.

9
Aron, G. and G. B. Emmanuel. 1983. Evaluation of Drought Potentials and Damages in the Northeastern United States. Pennsylvania: The Pennsylvania State University, Institute for Research on Land and Water Resources.

This report investigates the various impacts of drought and analyzes the means to avoid drought losses. The authors examined the cost incurred by Pennsylvania water suppliers during the 1980-1981 drought, however their attempt to estimate shortage-damage functions was impaired by nonuniformity of the suppliers' assessment of drought-induced costs.

Two alternatives for mitigation of the negative impacts of drought were proposed. The first measure involved optimal sizing of reservoirs through improved statistical frequency equations for various levels of drought. The second alternative was augmentation of streamflow by groundwater involving application of surplus streamflow to land along the streams during wet seasons to store water in the aquifers adjacent to the river bed. The latter alternative was recommended to be tested in practical experiments on a real site.

10
ASCE Task Committee on Water Conservation. 1981. Perspectives on Water Conservation. Journal of the Water Resources Planning and Management Division, ASCE 129(WR1):225-238.

This article constitutes a summary of the Task Committee's initial report on water conservation which was provided to the ASCE Committee on National Water Policy for use in preparing an ASCE statement for congressional hearings. The authors considered many aspects of water conservation including the level and specifics of emergency conservation planning.

According to the text (p. 228): "...the specifics of an emergency response program will vary with the geographical area, resource availability, the nearness of supplemental sources of water, and the economic and employment development in the area." In addition it is suggested that "initial steps of an emergency program might also be included as a part of normal conservation program" (i.e. effective use of limited resources).

A brief statement regarding the general characteristics of drought emergency programs follows (p. 228): "Emergency response programs generally increase savings, and are tied to the severity of the emergency condition. The problem during drought is to properly manage available resources. Emergency programs generally consist of: (1) Restrictions on nonessential use; (2) utilization of interconnection systems, if available; (3) restrictions on public use; (4) restrictions on industrial use; (5) restrictions on domestic use often coupled with significant charges for not meeting the limits imposed; (6) increased withdrawals from underground basins; (7) reducing the acreage of irrigated farm land planted; (8) changing agricultural cropping patterns; and (9) increasing agricultural water use efficiency. An emergency program will focus on who will be hurt by the shortage and the economic consequences. For example, in municipal systems, assuming adequate supplies are available for subsistence, there will be a strong desire to preserve jobs which means special consideration to economic impacts. While municipal programs may impose "mandatory" restrictions, the experience in many California communities was that they were really voluntary because of the lack of enforcement capability. Three requirements of an effective voluntary program are that: (1) Adequate information be made available on what to do; (2) the consumer clearly perceives the need; and (3) there be ample media coverage.

This article is a valuable guide for water conservation planning and it clearly defines the role of drought contingency planning within this conservation policy.

16

Berk, R. A., C. J. LaCivita, K. Sredl, and T. F. Cooley. 1981. Water Shortage. Cambridge, Mass.: Abt Books

This book provides a comprehensive analysis of the responses of 50 districts and communities in 9 California counties to the 1976-1977 drought. The analysis covered a range of drought-adjustment actions using time series data on water use and conservation activities.

The authors found enormous variation in the responses to the impending water shortage of various communities. They varied from no more than a single information leaflet in San Diego, to a broad water management plan introduced by the Mann Municipal Water District. The latter included mandatory rationing, distribution of water saving devices to residential customers, educational campaigns and a moratorium on new service connections. The overall findings of the study has been summarized in the following statements (p. 148):

1. Conservation programs will be more effective when consumers can be convinced that a genuine shortage exists and that it constitutes a problem for a group(s) with which consumers identify.

2. Conservation programs will be more effective when appeals are made to moral principles, stressing the need to make a "fair" contribution to group welfare.

3. Conservation programs will be more effective when consumers are convinced that their individual efforts can make a difference for collective welfare.

4. Conservation programs will be more effective when consumers can be convinced that the individual costs and inconveniences stemming from their conservation efforts will not be great (assuming this is true).

5. Conservation programs will be more effective when consumers are convinced that all members of the relevant group(s) are also making sincere efforts to conserve.

The book also contains a statistical analysis of the relationships between disaggregate water consumption and various indicators of conservation programs, price of water and variables controlling seasonal and climatic variation. The results showed that water consumption responds to both conservation programs and the price of water. The price elasticity for residential users was estimated at -0.23. The authors' attempt to explore the relative effectiveness of various conservation programs compared with price increases produced valuable information for developing drought contingency plans.

Overall, this book represents one of the most extensive studies of public policy responses in the drought literature.

19

Blackburn, Anne M. 1978. Management Strategies Dealing with Drought. Journal of the American Water Works Association 70(2):51-59.

This article reviews the steps taken in 1976 by the Thames Water Authority to deal with the worst drought in recorded history in the United Kingdom.

The first step taken by the national government was to establish industry, tourism and agriculture as having the first priority in receiving water. In addition, three main policies were adopted in order to alleviate the effects of water shortages. These included: (1) increasing flexibility of utilization of existing water supplies; (2) increasing available supply; and (3) agreeing on a four step demand reduction policy: voluntary reduction, mandatory conservation, banning non-essential uses, and rationing. These policies were included in the Drought Act which was adopted by the Parliment. The Act gave the river basin authorities the power to prohibit non-essential uses of water which included: (1) watering of parks, lawns and other recreational areas; (2) pool filling; (3) car washing including mechanical car washers; (4) cleaning of buildings; (5) operation of fountains; and (6) operation of automatic flushing system in unoccupied premises. In addition, information centers were set up throughout the country which carried massive educational campaigns.

The emergency actions taken by the different river authorities were varied. The Thames River Basin Authority virtually stopped the flow of the Thames River when it launched an extensive pumping effort in order to replenish its reservoir storage. On the demand side, a 20 percent reduction was achieved by voluntary conservation and 25 percent pressure reduction in the London distribution system. Also sewage effluent from London was made available to grass race-course owners at no cost when all outside uses of water were banned. The strictest conservation measure was introduced in South Wales where 17 hours per day cutoffs in water supply resulted in 50 percent reduction in normal water use.

This article is a valuable position in drought literature. It reports on numerous measures which have not been tried yet in the U.S.

20

Blackwelder, B., and P. Carlson. 1982. Survey of the Water Conservation Programs in the Fifty States: Model Water Conservation Program for the Nation. Completion Report Environmental Policy Institute, Washington, D.C., pp. 140.

This report presents the results of a survey of the water conservation programs in each of the fifty states. The objective was to determine whether each state had a formal water conservation program in each of the following conservation activities: (1) public education; (2) plumbing codes, (3) retrofitting with water-saving fixtures; (4) metering; (5) leak detection; (6) rate structures; (7) drought contingency planning; (8) resue and recycling; (9) outdoor use; (10) groundwater management; (11) industrial use; (12) agricultural use; and (13) government buildings and grants.

The report gives a brief description of significant state or local programs in each state. Among these the most comprehensive programs including drought contingency planning are being carried out in California, Massachusetts, Minnesota, and Maryland. Based on these and other programs the authors designed model programs for three different use categories which can allow reduction in water use (domestic and municipal) between 15 and 75 percent, and provide significant reductions in industrial and agricultural water uses.

24

Boland, John J., Philip H. Carver, and Charles R. Flynn. 1980. How Much Water Supply Capacity is Enough? Journal of the American Water Works Association 72(7):368-374.

This paper describes a study performed by the authors for Ecological Analysts, Inc., as a part of a larger investigation for the Washington Suburban Sanitary Commission.

The purpose of this article was to discuss the application of risk management techniques for determining the optimum level of supply reliability by examining the cost involved in decreasing the probability of water deficit. In arriving at the optimum solution, a range of scenarios for implementing drought contingency plans was examined against alternative long-term water supply projects "...to select the combination yielding the best compromise between, on the demand side, risk and the cost of water use restriction, and on the supply side, the economic, social, and environmental cost of providing increased capacity" (p. 373). Although the costs of water use restrictions were not evaluated, the alternative demand management plans were given a role as a substitute for the last most expensive increments of water supply capacity.

The analysis also included the development of probabilistic forecasts of water supply deficits from water-use forecasts and statistical analysis of water supply data.

27

Bowles, D. S., T. C. Hughes, W. R. James, D. T. Jensen, and F. W. Haws. 1980. Vulnerability of Water Supply Systems to Droughts. Utah Water Research Laboratory Report UWRL/P-80/08. Logan: Utah State University.

The purpose of this study was to develop 2 indices assessing the severity of drought and the vulnerability of a water supply system to drought which would be useful in water conservation planning. The authors used the following definitions of these indices:

1. drought severity index, S,

$$S = \frac{U}{D} = \frac{D-F}{D}$$

where U is the unfurnished demand, also defined as the total demand (D) less the furnished demand (F), and

2. drought vulnerability index V(S')

$$V(S') = Pr\ (S > S')$$

which is defined by the probability that the drought severity index (S) will exceed a critical value, S', at which significant economic losses will be experienced.

These drought indices were evaluated for 3 municipal and 3 irrigation water supply systems in Utah based on historical water-use and supply records. The authors concluded that in order to define the effects of water shortage, a continuous loss-function would be more appropriate than the existing assumption that drought-related losses occur suddenly at a certain degree of water shortage.

The report also describes in general terms the impact of Utah's 1977 drought on municipal and rural water systems with respect to their size and examines 5 stochastic streamflow generating models.

31
Bruvold, William H. 1979. Residential Response to Urban Drought in Central California. Water Resources Research 15:1297-304.

The objective of this study was to identify residential responses to the 1976-77 California drought through analyzing (1) consumer evaluation of conservation programs mounted by water districts, (2) the effectiveness of conservation programs based on customer billing records and conservation measures adopted, (3) testing preliminary hypotheses which relate belief to behavior, and (4) assessment of consumer preference with respect to local versus regional (San Francisco Bay area) water conservation programs.

Residential consumers in 9 selected water districts were interviewed during the summer of 1977. The respondents' selection was based on a cluster sampling technique which produced 100 respondents in each study area. A carefully designed interview schedule was used for interviewing 50 female and 50 male respondents, with 50 over 35 years of age and 50 from 18 to 35 years of age in each district. Information about water conservation programs was obtained through visiting 27 water service districts or purveyors.

Results showed that water conservation and rationing programs instituted by districts were generally judged quite fair and effective. The concern over fairness was centered upon the use of per capita allotments, while effectiveness concerns were centered upon clarity and

communication of the conservation plan. Data on water use showed that rigorous residential conservation programs were able to reduce average use during summer months of 1977 by 50% or more (to 80 gpcd or less) as compared to the summer of 1976. Moderate rationing and mild conservation programs could reduce this by about 37% (to 100 gpcd or less), and by 20% to 130 gpcd or less), respectively. A belief index of the drought seriousness was the best predictor of personal conservation efforts. Finally, based on the interview results, a majority of respondents favored local rather than regional water conservation programs.

This work constitutes a useful example of a technique for determining social acceptability of water conservation measures and also contains valuable information on implementation conditions.

32
Buchanan, T. J. and B. K. Gilbert. 1977. The Drought. Water Spectrum 9(3):6-12.

This paper provides an overview of the many impacts of the 1976-1977 drought in various regions of the United States. The authors review the status of streamflow and groundwater, water quality and water supply. The detrimental effects of water shortages on domestic, municipal, industrial and agricultural uses as well as undesirable environmental effects are also discussed.

34
California Department of Water Resources. 1976. The California Drought--1976. California.

This report discusses the effects of the California drought and the measures that were proposed at that time. Areas described include agriculture (both dry-farming and irrigated), the State Water Project, the Central Valley Project, the Delta Urban areas, recreation, fish and wildlife, forestry, energy, and groundwater. Of special interest are the discussions of the early planning of the conjunctive use of groundwater and the water exchange with the Metropolitan Water District of Southern California. These measures proved to be very important in dealing with the drought later in 1976 and 1977.

35
California Department of Water Resources. 1977. The California Drought 1977--An Update. California.

This publication summarizes the overall impact in California of the drought in 1976 and adds an update to the status of drought conditions as of February 1977. A review of the weather conditions precipitating the drought was given followed by impact statements of the 1976 drought. Impacts were examined on a statewide basis as well as regional and resource

impacts. Water availability in 1977 was also examined. Plans for drought management in 1977 were outlined in economic and managerial terms. There were little actual water conservation data, as this was not the purpose of this publication. Appendix E contains information bulletins that contain information about technological appliances and their water-saving properties.

The report is a concise and comprehensive survey of the drought in California and the prescribed steps needed to alleviate the pressures of the drought. The information provided by the report may be helpful for the preparation of drought contingency plans.

39

California Department of Water Resources. 1978. Proceedings, Conference on Industrial Water Allocation and Conservation in California. Concord, and Los Angeles, California.

This volume constitutes a compendium of information for industrial water managers compiled from the proceedings of the drought conference on industrial water allocation and conservation held in July 1977 in Concord, and Los Angeles, California. It contains short problem presentations and discussions grouped under the following headings: (1) statewide drought response, (2) statewide water supplies quality, (3) Northern California industrial water supplies, (4) Southern California industrial water supplies, (5) local agency drought response, (6) industrial conservation programs and techniques, and (7) financing industrial water conservation.

Papers dealing with industrial conservation programs and techniques may be helpful in identifying applicable measures for industrial users of municipal water.

40

The California Governor's Drought Emergency Task Force (1978). 1978. Drought Alternative Strategies for 1978. California.

This report outlined the effects of the drought on California in 1976 and 1977 and recommended actions which should be taken if the drought had continued into 1978. It was anticipated that if the snowpack and rainfall of the 1977-78 winter were as low as that of 1976-1977, the effects would be worse than in 1977 but not catastrophic. Agriculture had almost as many irrigated acres in production in 1976 and 1977 as before but with different cropping patterns and with groundwater depletions averaging 4.2% and 8.4% in each of the years. Higher pumping and well-drilling costs were substantial. Agricultural losses were estimated at $800 million. Continued drought would bring further groundwater depletion.

Based on the 1976 and 1977 experience, municipal deficits up to 50% were considered manageable. Continued drought would necessitate water hauling (tank truckers) to many small communities but not at unmanageable proportions. Electric brownouts and blackouts could be avoided in 1978 (as they were in 1976 and 1977) but replacement of hydro water with fossil

fuels is expensive. The fish, wildlife, and forestry situations have been bad and will be worse and will require special attention. In Northern California, recreation has been displaced to the delta and to Donner and Tahoe. Removal of exposed sags and temporary launch facilities are needed. The issues considered in the report are important for drought contingency planning.

43

Clarke, K. F., C. Page, and J. S. Brew. 1980. Reliability of Water Resources. Journal of the Institution of Water Engineers and Scientists 34(1):61-73.

The authors of this article propose an alternative approach to determining the reliability of water supply and illustrate it within the case study of the Anglian Water Authority supply system in England.

In this approach the concept of "safe yield" is replaced by the "level of service." The latter represents the reduced level of supply during times of depleted reservoir storage designed to increase reliability of the system. The reduced supply is achieved by introducing an operating strategy that imposes various demand reduction measures keyed to the amount of water in storage. As a result, the level of risk is defined as the probability of the reservoir emptying, once the most severe restrictions have been introduced. New additions to supply capacity are required when the "level of service" drops, due to increasing demands or other factors, to an arbitrarily established "critical level of service" representing the minimum level of service which is acceptable.

The authors believe that although this method does not explicitly consider the cost of periodically implemented water use restrictions, it may lead to more efficient utilization of reservoir capacity. The drought emergency measures considered for inclusion to the AWA operating strategy were (p. 63):

(a) bans on the use of hosepipes for watering private gardens and washing private cars, accompanied by appropriate publicity;
(b) large scale publicity campaigns to induce voluntary savings, coupled with restrictions on inessential uses;
(c) reduction by 50 percent of the statutory minimum prescribed flows (MPF) at the river intakes to pumped storage reservoirs, thus making more water available to pump into the reservoir; and
(d) the use of standpipes in the streets, or rota cuts in supplies to different areas.

A simulation analysis for various levels of service involving implementation of the above measures showed that the data at which first supply addition is required ranged from 1988, for the least frequent implementation of water use restrictions, to 2011 for the most frequent restrictions.

46
Crews, James E., and William E. Trieshman, Jr. 1979. Drought Effects on Metropolitan Washington, D.C. Area. In Proceedings, Conference on Water Conservation Needs and Implementing Strategies, pp. 156-64. New Hampshire: Franklin Pierce College.

The authors described the drought history in the Potomac River Basin and efforts designed to assist in preventing or reducing severe drought impact on water users in the Washington, D.C. area. Three major utilities in the area, the Washington Aqueduct Division (WAD) of the Corps of Engineers, the Washington Suburban Sanitary Commission (WSSC), and the Fairfax County Water Authority (FCWA) signed a low flow allocation agreement which allocates among them the Potomac River's water during time of a drought. However, because during a drought water supply may be still insufficient, Metropolitan Washington Council of Governments (MWCOG) and water utilities are in the process of adopting comprehensive plans for necessary curtailment of water use and other emergency actions during a water shortage.

These plans are designed to obtain maximum demand reduction reaching 60 percent of normal use. The WSSC plan is comprised of the four increasingly stringent stages in water use reduction. These are: (1) a 5-25 percent reduction through curtailing outdoor use; (2) a 25-40 percent reduction achieved by limited indoor use; (3) a 40-60 percent reduction achieved by curtailing the commercial and industrial use; and (4) over 60 percent reduction through the most severe restrictions imposed on all water use categories. The FCWA plan adopted a six-stage plan to reduce water use during emergencies including the following measures: Stage I - voluntary reduction; Stage IIA - minimum hardship or economic loss measures; Stage IIB - restrictions on all outdoor use; Stage IIC - reducing public water use indoors; Stage IID - reducing public use in certain commercial establishments; and Stage III - ban on non-essential water use (all uses except for the health and safety of people).

In general, the paper demonstrates an increased flexibility in balancing supply and demand when water conservation is introduced as an acceptable alternative to providing additional supply capacity.

47
Curtis, David C., and John C. Schaake, Jr. 1979. The NWS Extended Streamflow Prediction Technique. In Proceedings, Conference on Water Conservation Needs and Implementing Strategies, pp. 182-95. New Hampshire: Franklin Pierce College.

The authors presented the newest technique developed by the National Weather Service for water supply forecasting and for long-range streamflow forecasting in general called the NWS Extended Streamflow Prediction model, or shortly, ESP.

The technique utilized a subset of the collection of hydrologic, hydraulic, and data processing functions known as the National Weather Service River Forecast System (NWSRFS) which included (1) mean areal precipitation (point estimates of precipitation are transformed into areal

averages); (2) mean areal temperature; and (3) mean areal evapotranspiration. Three computational elements of ESP were (1) the Sacramento soil moisture accounting model generating five components of flow to the channel (direct and surface runoff, interflow, and primary and supplementary base flow); (2) snow accumulation and ablation model utilizing estimates of air temperature; and (3) channel routing. The data required by the model include (1) hydrological model parameters, (2) initial basin conditions, and (3) representative future time series inputs in the form of areal means of precipitation and temperature over the basin.

Two examples of the use of ESP for water supply forecasts were also presented (San Joaquim Basin, California; Occoquan Reservoir, northern Virginia).

The techniques presented here are of critical importance for estimating the risk of water shortage at each stage of a drought.

54
Draper, S. H., R. N. Palmer, D. P. Lettenmaier, and S. J. Burgess. 1981. Water Resource System Reliability Under Drought Conditions: The Seattle Water Supply System as a Case Study. Technical Report No. 72. Washington University, Seattle.

This report examines the potential for reducing the vulnerability of water supply systems of the Cedar and Tolt River of Western Washington to drought through improved management and planning. The drought management tools examined included:

(1) drought indices including Palmer Drought Index to forecast hydrologic drought;
(2) hydrologic runoff forecasting methods; and
(3) simulation modeling.

A detailed simulation model of the Cedar/Tolt system, formulated in the study, revealed that characterizing system reliability in terms of supply deficits had many advantages over conventional safe yield analysis.

57
Edmonds, L. A., and S. L. Bishop. 1982. Planning for Droughts. Consulting Engineer (St. Joseph) 59(3):90-94.

This article summarizes the major elements of drought contingency planning. The actions which the authors suggest for consideration by water suppliers include:

(1) obtaining and frequent updating information on existing water supplies and water usage;
(2) reducing unnecessary losses of water from the system;
(3) formulating an emergency demand reduction program utilizing water use restrictions and active citizen education element;

(4) identifying and evaluating emergency sources of water supply; and
(5) intelligent managing of water supplies to optimize utilization of existing sources, including the revisions of rate structures, to promote equitable and efficient use.

The article also reviews water plans adopted for the cities of Gloucester and Rockport, Massachusetts.

67
Fulton, George P. 1981. New York's Water Supply Dilemma. Public Works 112(2):55-59

The author considers the threat of drought-induced water supply shortage in the New York metropolitan area. Since the drought of the 1960s, no significant additions have been made to the capacity of the water supply sources while usage has risen about 20 percent. During a minor drought of 1980 the city reservoirs were holding about 45 percent capacity in September compared to an average of 70 percent for that month. During the drought of 1960s voluntary conservation saved about 200 mgd, however, the author doubts if such reduction can be achieved again.

In order to alleviate the potential shortage of water in 1980, serious considerations were given to a number of drought management alternatives. Substantial additions to supply capacity are not feasible due to the fact that both the Hudson and Delaware Rivers have been highly developed and any further development would be too costly. Only "high-flow skimming type developments" are considered feasible. These include: (1) the reallocation of water between existing reservoirs; (2) gravitational diversions of water from high grounds to already constructed reservoirs; (3) pumping water from a river at high flow periods to existing storage facilities; and (4) construction of small reservoirs to divert water from small streams.

The author concludes that because of increasing consumption a formal drought contingency plan should be developed.

68
Garland, Sidney, B. II. 1975. Water Rationing on Okinawa. Journal of the American Water Works Association 67(2):296-297.

This short article reports on an effective rationing method adopted by the Integrated Island Water System (IIWS) on Okinawa, Japan. This method consists in the turning-off of water supply for 24 hours and turning on for the subsequent 24 hour period. On off days water is to be delivered only to hospitals, milk plants, ice plants, and cold storage, other users have to store water for potable and nonpotable use.

This rationing method is coupled with a public education campaign which publicized the following conservation methods (p. 297):

1. Only store the amount of water needed.
2. Do large laundry loads and save rinse water for nonpotable use.
3. Heat water for shaving to prevent wasting water until it is hot.
4. Place bottles or bricks in toilet tank to reduce water use at each flush.
5. Repair plumbing leaks immediately.
6. When showering - wet-down, soap-up, rinse-off, and save rinse water.
7. Collect rain water, dehumidifier water, and air conditioner water for nonpotable use.
8. Flush toilets only when absolutely essential. In public areas, such as schools, do not allow users to flush toilets, custodial personnel or some designated person should do this periodically.
9. Do not water lawns or wash car unless necessary.
10. On days when water is on, do not relax conservation measures.
11. Reuse water from rinsing dishes and vegetables for flushing toilets.

To prevent waterborne-disease outbreaks during rationing, the IIWS instructed the residents in emergency water disinfectant with household bleach and through boiling. No estimates of the effectiveness of this rationing method were provided by the author.

69

Gilbert, Jerome B. 1978. The California Drought--Out of Disaster, Better Water Management. Journal of the American Water Works Association 70(2):79-81.

This article considers the possible benefits that California gained from the 1976-1977 drought. The author briefly summarized the major responses of the state to the crisis including: (1) water rationing reaching up to 50 percent cutbacks in normal water use; (2) formation of several agencies to manage the drought emergency actions; (3) permitting higher than usual environmental risks by reducing the releases to maintain minimum flows in the Sacramento and San Joaquin Rivers; and (4) setting new priorities for wastewater reclamation.

The drought experiences helped identify several major areas that needed special attention. These included: (1) the need for a comprehensive water management plan; (2) the need for interchanges between water systems and efficient water use; (3) the need for cooperation among local, state, regional and federal agencies in providing water transfers; (4) the need for consideration of multiple water use projects; and finally (5) the need for lowering environmental quality standards during drought emergency.

The author points out the crucial areas of water management that, if studied and improved, would greatly increase the overall efficiency of water use in California. When implemented, the appropriate long- and short-term management plans would enable the state to sustain a major drought.

70

Glantz, Michael H. 1981. Consequences and Responsibilities in Drought Forecasting. Water Resources Research 18(1):3-13.

This paper reports on the implications of an erroneously calculated estimate of the total water supply available (TWSA) made by the Bureau of Reclamation, for water users in the Yakima Valley, Washington, in February 1977. In response to this forecast, and subsequent allocations of water, the irrigation districts and individual farmers took a variety of measures to cope with the predicted shortage of water. These included: (1) drilling new wells at a total cost of $9 million; (2) leasing water rights; (3) conducting feasibility study for diverting water from the Columbia River at $70 thousand; (4) constructing pumping station to use dead storage at a cost of $3 million; (5) cloud seeding at a cost of about $500 thousand; and (6) other activities such as water banking, storage sites, farm subsidies, water transfers and other. All of these actions were unneeded and many farmers took legal actions against the Bureau to recover their costs.

This study provides a valuable insight into the problem of drought forecasting. It raises the questions about the benefits to society of good forecasts and the costs of societal responses to erroneous ones.

72

Griffith, Evan L. 1978. Southern California's Drought Response Program. Journal of the American Water Works Association 70(2):74-78.

This article summarizes the response of the Metropolitan Water District (MWD) of Southern California to the drought of 1976-1977. The MWD serves about 5,000 square miles of coastal plain stretching from Oxnard to the Mexican border.

The MWD's response to the drought included both replenishing the dwindling water supplies as well as reducing the amount of water used. This was achieved by increasing the amount of water pumped from Colorado River aqueduct and by reallocating water storage among reservoirs. More equitable groundwater and basin management also helped to replenish some of the water supplies. The MWD also undertook a vigorous program to reduce water consumption which was comprised of four major steps: (1) informing the public through mass media "to let people know water conservation is essential;" (2) rationing and introduction of surcharges (when rationing was not yielding results water rates were doubled for those customers who used more than 90 percent of what they used in the preceding year); (3) introducing economic incentives (the MWD gave over 3 million dollars in $20 credit for water use below the 90 percent level); and (4) adopting ordinances to outlaw nonrecycling decorative fountains, washing down paved surfaces and wasteful uses of water. The effectiveness of these measures was judged very successful. It was estimated that the citizens of the MWD service area were conserving about 10 to 15 percent compared with the 1976 usage. The city of Los Angeles achieved savings of more than 20 percent while being on a 10 percent mandatory rationing program.

The author concludes that the drought brought close cooperation and coordination between agencies and institutions concerned with water

resources in Southern California. Such a cooperation is seen as a necessary condition for any drought response program to be successful.

73

Groopman, Abraham. 1968. Effects of the Northeast Water Crisis on the New York City Water Supply System. Journal of the American Water Works Association 60(1):37-47.

This article describes the activities of the New York water system in response to the 1966 drought.

In April 1965 a water conservation program was instituted which included intensive appeals for voluntary conservation backed up by restrictions on the non-essential uses. Appeals were made through the mass media, door-to-door solicitation, sound trucks, and handouts of flyers and bumper stickers. Based on water use data from 1949-1950, it was judged that water consumption decreased by 20 to 25 percent.

80

Harnett, John S. 1978. Effects of the California Drought on the East Bay Municipal Utility District. Journal of the American Water Works Association 70:69-73.

The author's purpose was to describe the effects of the 1975-77 drought and how the East Bay Municipal Utility District coped with them. The utility serves a population of more than 1 million on an eastern side of San Francisco Bay. By March 1977 the Pardee Reservoir, the only impounding reservoir in the area, was filled to 22 percent capacity, 112 feet below the spillway. Because of reduced withdrawal and an additional amount of water from inflows, it was at 36.5 percent capacity at the end of Fall 1977.

On February 8, 1977, a water-rationing plan was adopted, aimed at an overall reduction in water consumption of 25 percent. Residential customers were allotted 280 gpd, industrial customers were cut 10 percent, commercial and public use cut 25 percent, apartment complexes cut 30 percent, and on-residential irrigation cut by 50 percent. The District also adopted specific prohibitions against wasteful usage. By April 1977, further reductions were needed to aim for adjusted overall reduction of 35 percent. Water rates were increased and an excess use charge was established. Customer response was immediate and usage dropped in February and March. Newsletters and other publications were used to disseminate information. By June 1977, water was also pumped in from Sacramento to the San Joquin Delta by merging construction of installations.

The author suggests that in selecting numerous options, all factors should be weighed, the public should be extensively involved, and that the program must be administered fairly and firmly. The program adopted must provide "an appeal procedure" to maintain public support. A non-drought

conservation program was highly recommended as it keeps both the customers and the utility aware and ready to deal quickly with a water shortage. The article points out reduction of usage by 35 percent within just a few months. The implications of relatively permanent reductions in water usage as a result of technological change during the crisis period are important from a long-term conservation point of view.

81
Harrison, R. 1977. Response to Drought. Water Spectrum 9(3):34-41.

This article summarizes the detrimental effects of drought conditions during 1976-1977 on western states followed by the discussion of potential measures needed to mitigate water shortages. The suggested solutions for dealing with drought in the long-run are: (1) modernizing irrigation systems (from 5 to 25 percent of water is lost from old systems); (2) reallocation of water rights; (3) increasing the number of wells; and (4) cloud seeding. Short-term solutions included such conservation measures as reducing lawn sprinkling, car washings, and the filling of swimming pools.

The author suggests that even though agriculture uses the majority of water in the West, residential water conservation is the best short-term solution to shortages because the former usage requires substantial investments in improving and altering the irrigation methods. An average usage of 200 gallons per capita per day in the drought stricken areas of the West can be reduced by half through an effective conservation program. Also, the industry can achieve reduction in water use by 25 percent without incurring substantial economic hardship, as evidenced in California.

Overall, the article gives a good overall perspective on the impacts and mitigation of droughts in the United States.

91
Hoffman, M., R. Glickstein, and S. Liroff. 1979. Urban Drought in the San Francisco Bay Area: A Study of Institutional and Social Resiliency. Journal of American Water Works Association 71(7):356-363.

This case study had 4 objectives: (1) to identify the ways of arriving at drought emergency decisions; (2) to identify the policymaking process in selecting coping strategies; (3) to assess the effectiveness, cost equity, and administrative feasibility of different drought policies; and (4) to identify changes in water management practices as a result of the drought experience. The study extracted information from 8 agencies supplying together approximately 1 million acre-ft of water per year in the San Francisco metropolitan community.

The analysis showed that 2 factors have contributed to the unpreparedness of the utilities to supply shortage: (1) the relatively short time frame in which policymakers must reach decisions about the

extent of precipitation, and (2) the staff's conviction that dry years are not persistent. Among factors influencing the formulation of drought policies, the most important were equity and public perception of the respective conservation programs. Revenue considerations and administrative convenience played a secondary role.

The strategies chosen by the districts to augment supply (such as emergency surface supplies, dead storage, new wells, leak detection) were generally unsuccessful in producing additional water, and their costs were approaching $\$0.24/m^3$ ($0.91/1000 gal). Interdistrict transfers, although producing considerable increments to supply, were very costly, i.e. up to $\$0.60/m^3$ ($2.27/1000 gal). The most successful management strategies were those of cross-purpose water diversions involving the curtailment of elimination of hydropower generation with direct costs less than $\$0.04/m^3$ ($0.15/1000 gal); however, their indirect costs were substantial.

Demand reduction strategies involved voluntary cutbacks on consumption requested by 3 districts and mandatory rationing imposed by the other 4. The degree to which residential, and to a lesser degree commercial and industrial, consumers were willing to restrict their water use was found to be influenced by the degree to which they believed there was a shortage requiring conservation. Resulting behavioral changes were found to be 3 to 4 times as effective as structural devices in lowering residential consumption. The costs of demand reduction for the 4 districts employing mandatory rationing varied from $\$0.05/m^3$ ($0.19/1000 gal) to $\$0.25/m^3$ ($0.95/1000 gal). These include costs to residential consumers which were primarily landscaping losses. A survey of landscapers in one district showed that these losses ranged from 0 to $400 per single-family dwelling unit.

The authors concluded that direct costs to augment supply ranged from 1.75 to 2.3 times the direct costs to reduce demand. However, in order to interpret these numbers properly, it was necessary to take account of cost resulting from lost revenues because of reduced water sales and reduced hydropower. The foregone external opportunity costs caused by reduced water sales were $4.3 million for the East Bay Municipal Utility District and $2.5 million as a loss in power sales by the San Francisco Water District.

92

Hogarty, Richard A. 1971. The Metropolis Runs Dry. Journal of the Irrigation and Drainage Division ASCE. 97(IR4):559-570.

This article analyzes the jurisdictional and political problems that arose in response to the drought of 1961-1967 in the states of New York, New Jersey and Delaware. During that period precipitation fell 25 percent below normal and the streamflows were at an all time low. By 1964 the drought prompted major responses from the local, state and federal agencies of the inflicted areas.

In June of 1965, New York City withheld downstream releases from its Delaware-fed reservoirs. Claiming it was illegal, New Jersey took the

controversy to court, where it was decided to give total jurisdiction over the river to the newly created Delaware River Basin Commission (DRBC). The Commission made efforts to reach agreements between the different state agencies on water rights, jurisdictions and water supply projects. After months of hearings, the DRBC set up a water bank designed to minimize streamflow downstream and maximize storage upstream. Also, an agreement was reached to tap the Hudson River which included the remodeling of several purification plants. Finally, the Federal government in 1966 passed legislation giving over one million dollars to the DRBC for reservoir construction.

On the local level, New York City responded by imposing water use restrictions such as prohibiting lawn sprinkling, car washing, filling of swimming pools and the hosing of sidewalks. Overall, these conservation measures achieved up to 200 mgd reduction in water use in the New York City area.

In summary, the article represents a valuable documentation of the unpreparedness of local, state and federal officials to handle the drought. The experiences of the drought pointed to the need for a regional solution in preparing a long-range regional drought management program.

94

Howe, Charles W., P. K. Alexander, J. A. Goldberg, S. Sertner, and H. P. Studer. 1980. Drought-Induced Problems and Responses of Small Towns and Rural Water Entities in Colorado, The 1976-1978 Drought. Colorado Water Resources Research Institute completion report No. 95. Fort Collins: Colorado.

The report documents the response of small towns in Colorado to the 1976-78 drought and makes recommendations concerning water rights transfers and conjunctive use management in response to future droughts. The authors obtained information on drought responses from 62 towns with average population of 3,300.

The drought responses were classified into two categories: (1) the short-term alternative actions; and (2) policies with long-term effects on water supply. The short-term drought management measures included:

(1) obtaining surface water on short-term exchange or cooperative basis from farmers and state fish and game officials;
(2) trucking in water;
(3) obtaining permission to change points of diversion in order to make better use of existing water allocations;
(4) cleaning out and repairing water mains;
(5) introducing rationing in the form of alternate day sprinkling, sprinkler bans, and the prohibition of outdoor uses;
(6) introducing rationing in the form of requested percentage reduction from previous year billing period or limitation to a fixed quantity per billing period; and

(7) raising water rates in one of the three ways: raised monthly flat rate, sharp increase in rate per 1000 gallons in metered towns, and introduction of increasing block rate structure in metered towns.

The most popular actions with long-term effects on water use were:

(1) raising revenues to provide funds for system repair and expansion;
(2) obtaining state and federal aid for system improvement and expansion;
(3) purchasing or acquiring additional water rights;
(4) installing water meters;
(5) supplementing surface supply sources with stand-by wells; and
(6) imposing local sales tax to help fund water system.

The authors concluded that the best way to deal with drought-induced water shortages is to revise the existing water law system thus allowing more flexibility in reallocating water among various communities. They also suggested that rationing may prove the most economical way of coping with infrequent deficits in water supply.

95

Howe, C. W., P. K. Alexander, and R. J. Moses. 1982. The Performance of Appropriative Water Rights Systems in the Western United States During Drought. Natural Resources Journal 22(2):379-389.

This study examined the actual and potential problems related to the performance of appropriation systems of water rights during periods of water shortage. The authors contrasted the water use practices under appropriations doctrine with the principles of economically efficient water allocation and identified several sources of inefficiency during drought.

In order to improve the efficiency of water allocation the following practices are suggested: (1) cooperative pooling of water; (2) water banking; (3) cooperative storage; (4) more flexible water ownership rules: (5) acquisition and administration of water rights by conservancy district; (6) developing a market in water rights; and (7) improving information and forecasting programs directed to specific areas.

99

James, L. Douglas, and Wade H. Andrews. 1978. Water Conservation Information Dissemination during the 1977 Drought Emergency. Utah Water Research Laboratory Planning Series report P-78-002. Logan: Utah State University.

This study was undertaken to provide for the exchange of drought information among the states affected by 1976-77 drought. The report contains 667 abstracts and a synthesis of the information obtained on each topic. The latter summarizes the content of the items collected on various topics and discusses the implication of that content for (1) extension programs, (2) government officials, and (3) researchers. The authors collected information on:

A. water-user conservation practices:

1. domestic use j (inside, outside),
2. industrial,
3. commercial,
4. irrigation;

B. water-supplier management practices:

1. water conservation inducements,
2. emergency water supply augmentation (groundwater mining, water harvesting, water reuse),
3. reallocation among uses or users;

C. dealing with special drought problems:

1. livestock and range management,
2. effects of fish and wildlife,
3. fire danger,
4. effects on recreation,
5. energy effects (reduced generation and additional use),
6. effects of resulting changes in water quality including salinity, and
7. wind erosion.

This publication is one of the primary references for designing short-term water conservation programs for drought contingency.

100

Jezler, Harold. 1975. When the Reservoir Almost Went Dry. Journal of the American Water Works Association 67:331-35.

This article describes the activities of the COMASP (water authority for Sao Paulo, Brazil) during a drought. Among these activities was a 2-stage water-use reduction program. The first stage consisted of public appeals with some rotating cutoffs to some zones. No mention was made of fears of infiltration as a result of these cutoffs. After 30 days, these recommendations were made mandatory with specific uses prohibited (no outside use of water) and with specific limitations for total water use by residences. Instructions were given on how to keep water consumption within legal limits. Only in a few (but well-publicized) cases was a 3-day cutoff of water supply imposed on residences. As a result of these efforts, average water use was reduced from 57 to 42 gpd (a 26% reduction). No major serious complaints were noticed.

102

Johnson, D. H., E. G. Brown Jr., and R. R. Robie. 1979. Impact of Severe Drought in Marin County, California. California Department of Water Resources Bulletin 206.

This bulletin describes the response of the Marin County citizens to water conservation restrictions imposed during the 1976-77 California drought, evaluates the effectiveness of the water rationing program, and determines the drought-related economic and social costs and losses. In the conclusion, the aftermath of the drought is discussed.

The information provided by authors may be used in determination of social acceptability and effectiveness of these short-term water conservation measures.

104

Kinsley, Ray K. 1982. Social and Political Aspects of Drought. Bulletin of the American Meteorological Society 63(6):586-592.

The author gives an overview of the social, economic, and political impacts which result from the effects of a periodic precipitation deficiency on activities within the affected region. He defines drought as "a period during which the water supply of a region is inadequate for the uses to which it is allocated," (p. 586) and points to three causes of a drought. These are: (1) meteorological drought which results from a period of abnormally low precipitation often accompanied by unusually high potential evapotranspiration; (2) climatological drought which exists in areas where precipitation is always too low to satisfy local water needs; and (3) socio-political drought which is a water shortage resulting from poor management or over-commitment of local resources.

As an example of socio-political aspects of drought, the author notes that "the threat of drought increases as consumption of water rises relative to the natural supply," (p. 586). Irrigation of one hectare requires the amount of water equivalent to 5,500 persons using 10 liters per day, while in order to support an area with population density of 15,000 persons per square kilometer, more than 6,000 millimeters of rainfall are required.

The author concludes that we may look to increasing problems of drought if the available water resources are overused.

110

Lampe, Les K. 1982. A Drought Alert System for Kansas Public Water Supplies. Department of Civil Engineering Report, University of Kansas.

The purpose of this report was to develop a drought alert procedure for Kansas based on a drought index called Basin Climatic Index. The BCI is calculated from the following formula:

$$BCI_m = 115 \sum_{i=1}^{m} \frac{P_i}{(T_i - 10)} \quad 1.11$$

where subscript m denotes the length of the period in months for which the index is calculated. P_i and T_i are, respectively, monthly precipitation in inches and monthly temperature in degrees Fahrenheit in month i of the m-month period. The period used by the author was 12 months.

The rationale for applying the 12-month running BCI's to predict relative availability of water for public water supplies was based on the dependence of supply sources on runoff, the magnitude of which can be related to the BCI. The report demonstrates the use of 12-month moving average BCI to predict the probability of various degrees of drought twelve months into the future. The prediction procedure utilized a relationship between predicted volumes of runoff during a 12 month period in the future and the 12-month moving average BCI for the last month. The forecast was made in terms of the probability of having less than a certain amount of runoff during the upcoming 12 months. The authors developed a series of curves which show the projected 12 month normalized runoff (expressed as a ratio of expected runoff to the long-term average runoff) in relation to the values of preceding 12-month BCI. Separate curves were developed for 10, 25, and 50 percent probability of occurrence for the nine climatological regions of Kansas.

The relative simplicity of the BCI method justifies its application as the first resort technique for assessing the likelihood of storage deficiencies for systems that rely on reservoir supplies. The statewide application of this procedure requires that long-term average BCI's are determined for various regions of a state and small water supply systems can use the forecasted runoff to assess their vulnerability to water shortage. Large water supply systems can perform all evaluations for the watersheds of their sources, thus improving the accuracy of the estimates.

113

Larkin, D. G., and K. E. Carns. 1979. Water District Revenue Implication of Conservation. In Proceedings, Conference on Water Conservation Needs and Implementing Strategies, pp. 204-210, New Hampshire, Franklin Pierce College.

This paper discusses the revenue problems suffered by the East Bay Municipal Utility District, (EBMUD) due to water conservation and other drought management programs in California during the 1976-1977 drought. Actions that were used by the EBMUD to alleviate water supply shortage included mandatory rationing, filter plant modifications, water reclamation projects, dam and spillway projects and major facilities for new supply developments totaling over 20 million dollars.

The demand reduction measures resulted in a 25 percent reduction in total water usage in 1976 and 35 percent in 1977. This caused the EBMUD to lose a substantial part of its normal revenue and an increase in water rates from $4.70/month to $7.00/month (average monthly water bill) was introduced to make-up for the lost revenue.

123

Meral G. H. 1979. Local Drought-Induced Conservation, California Experience. In Proceedings, Conference on Water Conservation Needs and Implementing Strategies, pp. 37-46. New Hampshire: Franklin Pierce College.

The purpose of this paper was to summarize the responses to 1976-1977 drought in California. Among conservation measures discussed by the author was the use of reclaimed water for the irrigation of landscapes at schools, parks and commercial establishments. An opinion poll revealed that 94 percent of homeowners were willing to use reclaimed water for their landscapes. Such practice could increase the available supply of water by an estimated 1,000 acre-feet per year.

The author also emphasized the effectiveness of water saving devices such as low-flow faucets, toilets, and showerheads. The use of these devices increased up to 27 percent during drought. Rationing programs were also successful achieving up to 36 percent reduction in per capita consumption in relation to normal rainfall years. Other drought management programs included temporary pipelines and the proposed construction of wastewater renovation plants.

The article concludes with a statement that water conservation was the most economical alternative in dealing with water shortages.

124

Miller, W. H. 1978. Mandatory Water Conservation and Tap Allocations in Denver, Colorado. Journal of the American Water Works Association 70(2):60-63.

This article discusses the program for water-use reduction undertaken by Denver's Water Board (DWB) in dealing with the drought in 1977. Below average precipitation, low snow pack in the Rocky Mountains and rising demand for water prompted the DWB to a three-part water conservation plan.

The first part involved increasing the DWB's service area to encompass more water sources, despite environmental concerns. The second part of the plan was to reduce by 30 percent the number of new water taps in various entities outside Denver. The third part of the plan was a mandatory water conservation program designed to limit the outside watering to a maximum of 3 hours every third day. This measure was enforced by department employees who issued 5,500 warnings and 238 ten dollar tickets for violations and was supplemented by a massive public education program. Over a four month

period July-October water use was reduced by 21 percent as compared to the previous 5 year average use for the same four months.

This article may serve as a prototype for formulation of sprinkling restrictions as a water conservation measure.

131

Morgan, Douglas W., and Peter Pelosi. 1980. The Effects of Water Conservation Kits on Water Use. Journal of American Water Works Association 72:131-33.

The authors reported on the effectiveness of a residential water conservation campaign which was undertaken by the City of Oxnard, California, during August 1977. The campaign involved free distribution of a 3-part water conservation kit. Each kit contained a toilet water dam, a plastic shower-head restrictor, and a packet of vegetable dye tablets to detect leaks from toilet storage tanks. One month after distributing about 3,200 kits, a total of 637 households were interviewed to determine the installation rate, socio-economic characteristics of households, water savings resulting from the installation of these conservation kits, and their cost effectiveness.

135

Motoko, Lee Y. 1981. Mandatory or Voluntary Water Conservation: A Case of Twelve Iowa Communities during Drought.

The author examined mandatory and voluntary water conservation policies adopted by 12 Iowa communities during the 1977 drought and compared these measures in terms of types of policymaking bodies, rationale behind adopting them, and quantitative evaluations of their effectiveness.

The analysis was based on 56 personal interviews with policymakers of the 12 communities who had participated in water conservation policy-making during the drought, and also on water-consumption data. The results showed that mandatory policies with per capita-based restrictions were most effective in reducing water consumption. Two of the 12 communities achieved substantial reduction with voluntary policies, which is explained by their proximity to communities where extreme shortages existed. The authors concluded that the credibility of water shortage is a key to successful conservation and recommended environmental education of citizens as a necessary policy to accompany long-run water conservation plans.

141
The National Water Council (Great Britain). 1977. The 1975-1976 Drought. London: National Water Council.

This report details the activities of the British water utilities to deal with the 1975-76 drought (the worst in recorded history since 1727). Of particular interest were the measures used to reduce water use. Generally these began with appeals which became more urgent over time. Public media were very helpful. Appeals combined with hosepipe bans typically achieved 20 to 25 percent reductions. Savings from pressure reductions were generally less than 10 percent. Leak-reduction programs saved approximately 5 percent in some areas. Industries were generally not closed, apparently in response to public sentiment concerning loss of jobs. In some cases rotating cut-offs or complete residential cut-off with standpipes provided was substituted with total savings to over 40 percent. Because most residences are not metered, rationing or fines for excessive use were not possible.

The council was satisfied with the amount of prior planning. More detailed planning, specifically rules as a function of rain or storage, were not judged to be useful. There are too many social factors that must be taken into account to use hard and fast rules. Implementation planning is very necessary for rotating cut-offs, standpipes and leak detection and pressure reduction. No health problems were encountered. Very few persons placed bricks in the toilet tank (9%) or installed dual flush mechanisms compared to the responses for pleas to cut in bath water, reuse water, flush the lavatory less, and stop watering garden (76-90%). Here advance distribution of water-saving devices would have been helpful. It is noted that the use of prohibitions and mandatory restrictions (hosepipe bans, pressure reductions, etc.) were effective not only in themselves but also in the re-enforcement of the crisis atmosphere necessary for voluntary water-use reductions.

The degree of adoption reductions in water use of these drought emergency measures may be used in developing drought contingency plans.

144
New England River Basins Commission. 1981. Before the Well Runs Dry -- A Handbook on Drought Management. Boston, Massachusetts.

This handbook describes a five-step procedure for developing drought contingency plans in small and medium-sized New England communities. The procedure is directed to water suppliers and local government officials who are faced with the need to alleviate the problems of a drought. The five basic steps involved in advanced drought emergency planning are (NERCC, p. 6):

1. Identify supply situation in relation to drought. Define goal and establish framework for sequential emergency measures.

2. Assess supply augmentation options.

3. Assess demand reduction options.

4. Develop plan for sequential emergency measures.

5. Select water-saving hardware/software.

The procedure was developed based on information gathered in an earlier study of NERBC on water conservation planning, which is published in two technical reports: (1) "Before the Well Runs Dry: Literature Survey and Analysis of Water Conservation, Volume I," and "Before the Well Runs Dry: A Handbook for Designing a Local Water Conservation Plan." Both reports were published in 1980. The handbook explains and illustrates the drought planning guidelines through application to a specific case study of Manchester, CT, where NERBC staff participated in developing a drought contingency plan. Despite its condensed format, this publication contains an excellent discussion of many issues involved in planning for water emergencies.

142

Nelson, J. O. 1979. Northern California Rationing Lessons. In Proceedings, Conference on Water Conservation Needs and Implementing Strategies, pp. 139-46. New Hampshire: Franklin Pierce College.

This paper reports on the effectiveness and acceptability of an emergency rationing of water during the 1976-77 drought in North Marin County Water District in California.

An emergency rationing plan for residential water consumption resulted in the reductions of between 25 percent and 40 percent. A serious water shortage and adequate communication with the consumers were considered deciding factors in this response. Reductions in commercial consumption up to 25 percent were also possible. Four distinct rationing procedures were used:

1. percentage reduction (compared to normal use in a previous similar billing period) - achieving 37 percent reduction,

2. seasonal allotment (a per capita or home allotment--increased in summer and decreased in winter) - a 25 percent reduction achieved, 5 percent below the intended goal,

3. fixed allotment (per capita or home allotment based on calculated need) - achieving a 65 percent reduction in water consumption, 8 percent above the intended goal, and

4. total sprinkler ban - achieving a 40 percent reduction, 10 percent above the intended goal.

The last method was found to be the least successful one in terms of compliance. For remaining techniques, rate penalties for exceeding allotments were not needed. In many instances where mandatory rationing was implemented, consumers cut water usage even more than requested.

145

Nicolson, G. S. 1979. Water Supply System Failures with Conservation. In Proceedings, Conference on Water Conservation Needs and Implementing Strategies, pp. 94-102. New Hampshire: Franklin Pierce College.

The author's purpose was to forecast annual reservoir failures with 2 sets of demands and situations for an existing water supply reservoir system using a computer model capable of simulating streamflow and reservoir operation.

Based on both the historic and synthetic streamflow records and also on water demand from the reservoir that was increasing 1 percent to 2 percent annually, and exceeding the long-term safe yield, the computer model was used to analyze the results of water conservation measures during forecasted drought. The results showed that for the considered reservoir system, forecasting and conservation had more impact on reducing failures when the probability of failure is high than when it is low. Failure probabilities of more than 20 percent and 10 percent were found for 2 simulation runs which had average demands of 0.85 maf and 0.79 maf, respectively.

148

O'Dowd, J. 1981. Northeastern New Jersey Grapples with a Drought. Public Works 112(6):74-77.

In the second half of 1980, densely populated Northeastern New Jersey was characterized by a severe drought causing the state to introduce mandatory water rationing as well as to tap fresh water lakes for auxiliary supply. To examine short- and long-term solutions to the drought the Water Emergency Task Force was formed including representatives of state and federal agencies.

A rationing plan was implemented restricting the amount of water per person to 50 gallons per day, while industries and businesses were mandated to reduce their consumption by 25 percent. On the supply side, the New Jersey officials considered two major pumping projects to use lake water to supplement dwindling reservoir supplies. One of these projects involved pumping water from Lake Hopatcong through a 2.5 miles long overland pipeline at a rate of 25 mgd for 100 days. It was estimated that the pipeline would be constructed in 30 to 40 days. Another project involved pumping water from Lake Wawayanda at a rate of 10 mgd for 70 days. The total cost of these projects well exceeded $2 million. Also a major pumping project was started to draw water from a 100-foot well in New York City to New Jersey at an estimated cost of $4 million.

The result of these considerations was an approval of long-term additions to the existing water supply capacity in the region.

157

Robie, Ronald B. 1978. California's Program for Dealing with Drought. Journal of the American Water Works Association 70(2):64-68.

This article reports on the measures taken in California to reduce water use during the 1976-1977 drought. In 1977 the average precipitation fell to 45 percent of normal, thus further intensifying the effects of precipitation deficits of the previous year. The effects of the drought were felt throughout California in the areas of agriculture, domestic water supplies, hydropower, wildlife and fire susceptibility.

The drought experiences revealed that: (1) there is a considerable water waste in California; (2) California's fresh water supplies are more limited than people realize; (3) most residents are ready to volunteer to conserve water, although rationing may be sometimes required; and (4) both industry and agriculture have large potential for conservation, but only residential conservation can be exercised during crisis situations producing substantial savings of water.

California's program for dealing with the effects of drought included ten basic steps: (1) forming the Drought Emergency Task Force which coordinated drought activities throughout the state and through other agencies; (2) setting up a state-wide education campaign; (3) implementing rationing programs in the troubled communities (some communities were alloted as little as 50 gallons per person per day); (4) imposing stiff penalties on users who violated conservation regulations; (5) arranging water exchanges and diversions between reservoirs and streams to divide the water more equally; (6) laying temporary pipelines to disperse water into troubled areas; (7) allowing farmers to store groundwater in aqueducts; (8) bringing higher quality water to wetlands to help out wildlife; (9) distributing water conservation kits; and (10) reducing public water use for parks and recreation through reduced landscape irrigation, and use of water saving devices. It was estimated that through these methods, 39 to 53 percent of water was saved in major population centers of the state.

This article may be useful in setting up a framework for drought management programs. It is also a valuable summary of drought experiences and their implications for better planning for droughts in the future.

158

Russell, Clifford S. 1979. Water Deficit Planning. In Proceedings, Southeast Regional Conference on Water Conservation and Alternative Water Supplies, pp. 209-19. Georgia: Georgia Institute of Technology.

The author sets out a planning framework for drought contingency programs with discussion of data requirements and limitations of such process. The three broad decisions considered by the author as constituting the essence of water deficit planning are (p. 212):

1. Deciding on levels of expected annual deficits (hence expected annual losses) in the long run, by balancing the costs of alternative system investment paths against the implied expected damages from drought.

2. Deciding when in the course of a particular period of rainfall shortage to introduce water-use restrictions (or other water-conserving measures) and thus to create a water shortage for consumers; a symmetric decision must of course be made about removing any measure once imposed;

3. Deciding on the actual measures which will be taken to reduce water use below normal demand by various amounts.

The first decision sets out the optimization criterion for the long-run, while the remaining two are directly related to short-term drought management strategies. The second decision involves "balancing chosen, and therefore certain, damages in the near term against unknown and uncertain--but possibly much larger--damages later in the period." (p. 214) Finally, the third decision utilizes the criterion for choosing among alternative conservation programs by finding "the packages of restrictions designed to achieve particular levels of use reduction...chosen so as to minimize the sum of the resulting losses and costs of implementation: publicity, monitoring, prosecution of offenders and so forth." (p. 214)

Discussing the data needed to back up these decisions, the author found that the most serious information gap resulted from (1) limited possibility of weather prediction over a long enough period of time to provide some basis for restriction decisions, (2) our limited ability to predict the responses of water use to price in the long- and short-run and thus future water demands, and (3) data inadequacies for estimating damages from water-use restrictions.

This paper provides an excellent treatment of the subject of drought contingency planning with its all implications for long-run water deficit planning.

159

Russell, C. S., Arey, D. G., and R. W. Kates. 1970. Drought and Water Supply. Baltimore: Johns Hopkins University Press.

This book describes the first study that made an attempt to place a value on reliability of water supply. The authors carried out a detailed investigation of the activities of 39 Massachusetts communities which suffered water supply shortages during the 1966 drought.

Among responses to the threat of shortage the most common activity was to place restrictions on water use and appeals for conservation. Thirty-four of the 39 communities restricted lawn sprinkling; of these 34, 10 banned all outside use. Thirteen of the 39 communities placed mandatory restrictions on industries (primarily recirculation) and 9 other "requested" or recommended recirculation. Nineteen communities also placed some restrictions on some public sector uses. Also reported was a study by Hudson and Roberts which indicated that 64 of 75 communities in Illinois that suffered shortages in 1953-55 placed restrictions on water use. Other methods of curtailing water use for short periods of time were not widely used in Massachusetts in 1966. Only 3 communities increased metering

activities or increased leak-detection programs. No communities increased price in response to the drought. It was noted that if the shortage were 10 percent or less, restrictions on industrial use were not likely to be imposed. No problems with enforcement were evident. In order to apprise the cost of drought, the estimates of economic losses attributable to the drought were developed for three towns: Braintree, Fitchburg, and Pittsfield.

The book also contains one of the best treatments of the problem of optimization in providing adequate urban water supplies with emphasis on drought performance of various supply systems. The analysis of this problem is performed using a comprehensive framework of concepts, definitions, and methodologies. The long-term investment model proposed by the authors is based on balancing expected drought losses as a function of specified level of system adequacy against the cost of adding increments of safe yield. The optimal timing and sizes of increments to the system's safe yield is defined for given rate of growth of demand so that it minimizes a total present value of capital costs and a discounted sum of expected annual drought losses within a planning horizon of 60 years.

160

Sabadell, J. E. 1979. Conservation Between and Beyond Droughts. In Proceedings, Conference on Water Conservation Needs and Implementation Strategies, pp. 196-200. New Hampshire: Franklin Pierce College.

The author briefly summarized the responses to the California Drought 1976-77 by the residential, commercial, industrial, and agricultural sectors. The highest reductions in water use were achieved in the urban residential sector.

Based on her analysis, the author made the following comments (p. 196):

1. The inevitability of droughts should be recognized and the appropriate drought management techniques should be an integral part of any water resources plan, development, or management scheme.

2. ...the manipulation of the natural conditions in arid and semiarid regions is limited not only by the primary and secondary ecological impacts of technological improvements, but also by economic, social and political controlling factors.

3. ...many regional systems are operating near or at their carrying capacity limit, the resilience of these systems is rapidly diminishing to the point of nonexistence.

4. Between and during droughts we have adopted two general types of decision-making: crisis, or "muddling through." The crisis response produces usually temporary remedies, has a short reaction time; the impact of that drastic event is seen as very hard; the stakes are perceived as high; and even regulations are put aside. In between

droughts, though, we tend to forget about what has happened during the dry spell and the benign neglect approach is the common practice...It is also believed that when the crisis comes again, some "fix", usually technological, will take us through the new episode with a minimum of harm."

The above remarks are relevant to the designing and evaluating drought contingency plans.

165

Schnizinger, Roland, and Henry Fagin. 1979. Emergencies in Water Delivery. California Water Resources Center contribution No. 117. Davis: University of California.

The purpose of this study was to evaluate the need for emergency preparedness, implementation methods, and disaster management procedures for water supply systems. The analysis involved a review of water needs in residential, institutional, industrial, and agricultural use sectors, and an examination of the nature of disaster with particular attention to public response and vulnerability of water systems.

The authors performed vulnerability analysis and evaluated emergency water allocation and system restoration policies for general models as well as for a particular geographical area in the San Diego region. The emergency operations which were investigated include: (1) recognition of an emergency; (2) communication and coordination; (3) allocation mechanisms; (4) the effects of rate structures; (5) restoration policies; and (6) mutual assistance. The site specific nature of emergencies is illustrated by selected case studies of emergency situations including earthquakes, the Trenton Water Crisis of 1975, and three recent droughts in the United States and England.

Many topics discussed by the authors are applicable to drought contingency planning.

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Sheer, Daniel. 1980. Analyzing the Risk of Drought: the Occoquan Experience. Journal of American Water Works Association 72(5):246-253.

The author describes an application of two practical techniques for determining the possibility of extreme water shortages in the Occoquan Reservoir (the primary source of water for the Fairfax County Water Authority) during the 1977 drought.

A simple first resort technique was used to assess the risk of the reservoir having gone dry dependent upon the current reservoir storage and soil moisture in the drainage area. The purpose was to determine in how many years in the historical record the reservoir would have gone dry given the demands and reservoir level as they were in 1977. The ratio of years

when the reservoir would have been empty over the number of years of record was assumed to measure the probability of running out of water in 1977. More precise technique, developed by the National Weather Service, was used subsequently to obtain more reliable estimates of risk.

The estimated risk of running out of water was approximately 15 percent (4 in 26 years). In order to reduce this risk, the FCWA has decided to implement increasing severe drought emergency measures keyed to the level of water in the reservoir. The last resort measure involved shutdown of schools and businesses. The risk of reaching the reservoir level triggering this measure was found to be approximately 10-15 percent. It was also determined that 14 percent reduction in daily water withdrawal would reduce this risk threefold.

The author concluded that both techniques were very useful in predicting streamflow and thus the expected availability of water supply which, in turn, provided valuable information for the development of policies necessary to reduce the risk of shortage to acceptable levels.

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U. S. General Accounting Office. 1977. California Drought of 1976 and 1977--Extent of Damage and Government Response.

This report reviews the effects of the 1976-77 California drought and the laws passed by the Congress and the State Legislature in response. Activities of some local irrigation districts and municipal water utilities were discussed. The report recommends the State plan be re-examined in light of the large expenditures ($4.3 billion Federal, $3.4 billion State) and the strong possibility that even these expenditures will not be sufficient to stop the need for overdrafting of groundwater. The report questions the advisability of the projected 1 million acre-feet increase in irrigation water use.

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Van Es, J. C., L. C. Keasler, and R. L. Whittenbarger. 1980. The Response of Illinois Municipal Water Systems to a Prolonged Period of Drought. Research Report No. 152. Office of Water Research and Technology, U.S. Department of the Interior, Washington, D.C.

This report analyzes the responses of 91 Illinois municipalities to the extended period of rainfall deficiency in 1976-1977. Of these municipalities 25 had to deal explicitly with the shortage of water. The information was obtained through a questionnaire survey of city majors and water system operators.

The survey revealed that: (1) 20 percent of municipalities attempted to find new sources of water through drilling new wells, purchasing water from another system or pumping water from nearby lake or river; (2) 87 percent of the 25 municipalities made attempts to improve the existing distribution system primarily through checking and repairing leaks; and (3)

all affected municipalities introduced one or more demand reduction measures.

Reducing demand proved to be the most often used and successful strategy in alleviating the effects of drought. The following is a list of demand reduction measures arranged according to the percentage of communities implementing such measures:

(1) voluntary restrictions on outdoor water usage;
(2) encouraging users to have obvious leaks repaired;
(3) voluntary restrictions on indoor water usage;
(4) voluntary installation of water saving devices;
(5) enforced ban on outdoor water usage;
(6) rationing water to industrial/commercial users;
(7) adjusting rates to discourage excessive use; and,
(8) rationing water to residential users.

The major recommendation of the study is that there is a need to develop a system of outside help to the small communities in order to improve their ability to deal with a crisis.

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White House Drought Study Group. 1977. March 1977 Drought Appraisal. Reprinted by the U. S. Army Engineers Institute for Water Resources.

This report describes the 1976-77 drought in California, Oregon, Washington, Idaho, and Nevada, and presents possible measures for drought management both in the short- and long-term. It was noted that in 1977, production on irrigated lands is expected to be 75 percent of normal. It was estimated that a comprehensive long-term conservation program in agriculture could achieve annual savings of 6 to 8 million acre-feet of consumption and 40 to 50 million acre-feet of withdrawals and that a 20 percent reduction in residential use could be achieved by the installation of water-saving devices. Short-term measures could reduce the average use per person by 50 percent. Tables of water conservation measures (agricultural and municipal) and a large number of tables, matrices, and maps describing the drought were presented.

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Young, G. K., T. R. Bondelid, and S. A. Daley. 1980. Methods for Water Supply Forecasting. Water Resources Research 16(3):556-564.

This article presents an alternative method to the NWS RFS extended streamflow simulation procedure. The authors propose a sensitivity analysis of the rainfall/runoff models used by the NWS model to determine the expected yield and the standard deviation yield for a given catchment. Instead of performing an extensive simulation of equally likely rainfall traces, the sensitivity approach uses only one typical trace of 6-hour interval rainfall data, current soil moisture estimates and variance of the rainfall input. The proposed technique requires less computer time than the NWS procedure.

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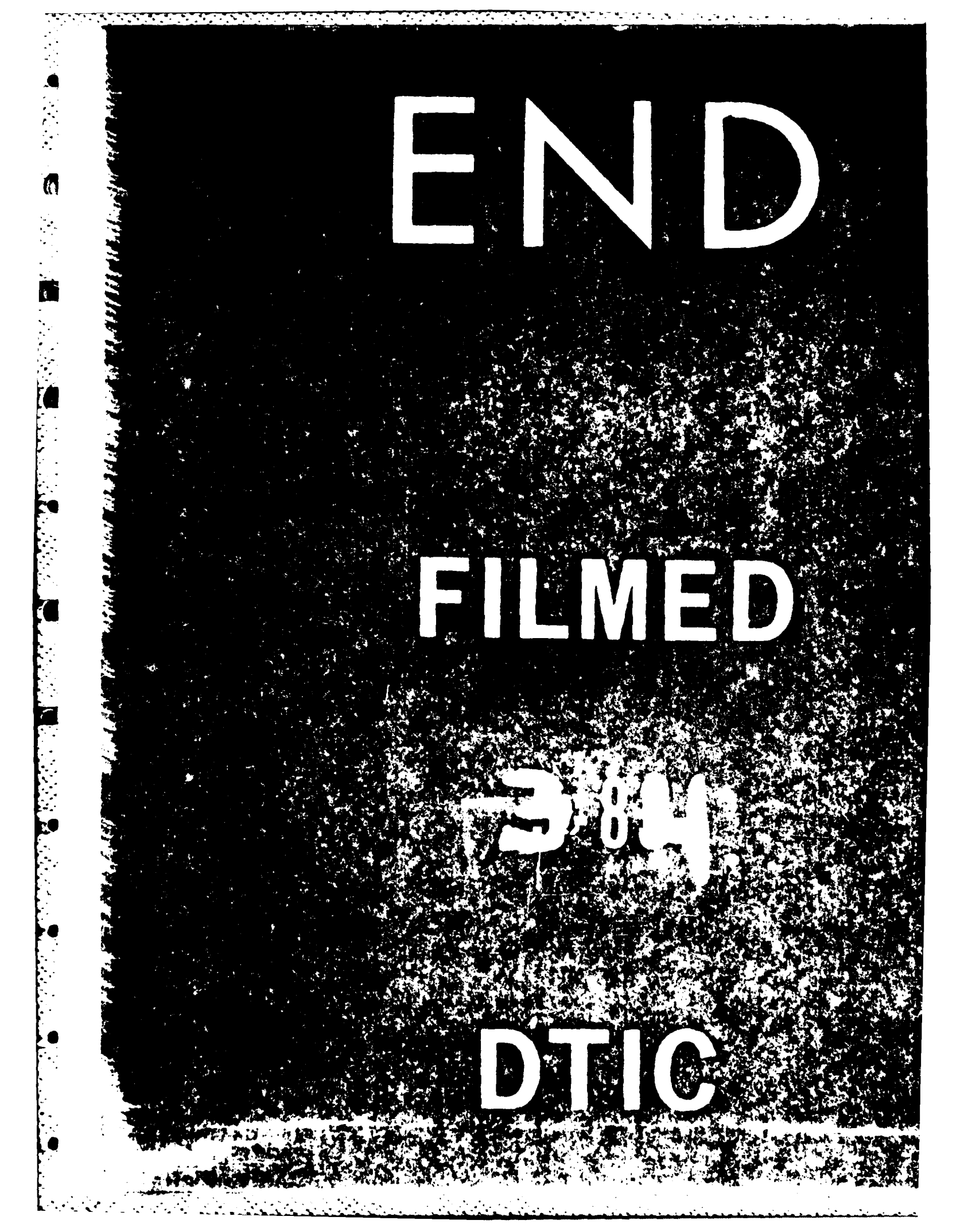
Young, G. K., R. S. Taylor, and J. J. Hanks. 1972. A Methodology for Assessing Economic Risk of Water Supply Shortages. IWR Report 72-6. Fort Belvoir, Virginia.

The purpose of this study was to develop a procedure for estimating income losses in residential, industrial, commercial, and municipal sectors associated with varying degrees of water shortage. The procedure was intended for estimating needs for supply additions as well as for allocating short supplies during emergency conditions.

The procedure was practically applied for the York Water Service Area in Pennsylvania. The optimization criterion used by the authors involved selecting the reservoir storage for which the sum of cost of storage and risk of shortage is at its minimum. The risk of shortage is defined as a sum of the products' projected values of annual regional losses and their respective probabilities of occurrence.

This report provides the most comprehensive practical methodology for optimizing reservoir system design. However, the weak point of the procedure is the prespecified drought contingency plan in the form of the decision schedule of a water manager who adjusts the quantity of water delivered according to the level of water in the reservoir. The authors recommend that further improvement is derived by finding the optimum short-term drought management plan that would minimize losses due to water shortage.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